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Sport, Health and Performance: Interdisciplinary Insights

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Sport, Health and Performance: Interdisciplinary Insights
Gyandev Anand
ISBN: 978-93-5590-556-7

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Asymmetries in the Technique and Ground Reaction Forces of Elite Alpine Skiers Influence Their Slalom Performance

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Abstract: Background: Although many of the movements of skiers are asymmetric, little is presently known about how such asymmetry influences performance. Here, our aim was to examine whether asymmetries in technique and the ground reaction forces associated with left and right turns influence the asymmetries in the performance of elite slalom skiers. Methods: As nine elite skiers completed a 20-gate slalom course, their three-dimensional full-body kinematics and ground reaction forces (GRF) were monitored with a global navigation satellite and inertial motion capture systems, in combination with pressure insoles. For multivariable regression models, 26 predictor skiing techniques and GRF variables and 8 predicted skiing performance variables were assessed, all of them determining asymmetries in terms of symmetry and Jaccard indices. Results: Asymmetries in instantaneous and sectional performance were found to have the largest predictor coefficients associated with asymmetries in shank angle and hip flexion of the outside leg. Asymmetry for turn radius had the largest predictor coefficients associated with asymmetries in shank angle and GRF on the entire outside foot. Conclusions: Although slalom skiers were found to move their bodies in a quite symmetrical fashion, asymmetry in their skiing technique and GRF influenced variables related to asymmetries in performance.

Keywords: biomechanics; kinematics; kinetics; global navigation satellite system; GPS; IMU; inertial motion capture; pressure insoles; ski racing

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1. Introduction

In connection with highly competitive elite alpine skiing, differences in finishing time are often very small [1]. Indeed, the overall finishing time is a major factor in determining a skier's FIS (International Ski Federation) ranking and it is therefore hardly surprising that analysis of gate-to-gate times has focused on determining where a skier loses or gains time in as much detail as possible [2,3]. However, although easy for coaches and athletes to understand [4], times on short sections of a course, such as from gate-to-gate, are not good direct indicators of either instantaneous or turning performance [5]. In this context, variables related to the dissipation of mechanical energy reflect kinetic performance more closely [5–7] and kinematic parameters related to the trajectory of the skis are also more reliable [8,9].

Although numerous descriptions of alpine skiing technique have been published, relatively little is yet known about the biomechanical factors that influence competitive performance [6]. One such factor is the start strategy, including the technique utilized and number of start-pushes [10]. Furthermore, the slalom skiing technique chosen exerts an impact on both ground reaction forces (GRF) and performance [11–13].

Thus, in the case of slalom, the larger the "attack angle" (i.e., the angle between the orientation of the skis and direction of skiing) when entering a turn, the more energy is dissipated [14], whereas with giant slalom, the choice of trajectory and smoothness of skiing during a turn are also major influences on energy loss and performance [7–9]. Furthermore, use of a more "dynamic" body posture reduces energy loss due to aerodynamic drag [15], although this is not a major determinant of the performance of elite giant slalom skiers [16]. Air drag is more important in super-G skiing and even more so when skiing downhill [17]. When skiing straight, the movement of the center of mass forwards and backwards does not affect skiing time, whereas the edge angle does [18].

Although the body movements of athletes, and especially those of left and right turns by elite alpine skiers, are often asymmetric, little is presently known about how these asymmetries influence performance [19]. Bell [20] and Hoffman [21] and co-workers have shown that asymmetries affect jump height, while Beck and colleagues [22] found that asymmetries in stride while running result in more consumption of energy. Although ski coaches are often concerned with eliminating such asymmetries (i.e., correcting "mistakes" made when performing the "worse" turn), to our knowledge, with respect to alpine skiing, only preferential usage of one of the legs is known to affect turning and the potential impact of asymmetry on overall performance remains to be determined [23].

Accordingly, our aim here was to examine whether asymmetries in technique and in the ground reaction forces associated with left and right turns influence the competitive performance of elite slalom skiers. Our hypothesis was that asymmetries in the performance of elite slalom skiers are influenced by asymmetries in their technique and in ground reaction forces.

2. Materials and Methods

2.1. Participants

Nine male slalom skiers, all members of the Swedish National Ski Team (age: 22.7 ± 3.4 y; height: 181.8 ± 6.9 cm; weight: 82.2 ± 5.6 kg; current SL FIS points: 24.9 ± 18.6 (means ± SD)), provided their written informed consent before participating in this study, which was conducted in accordance with the Declaration of Helsinki and pre-approved by the National Medical Ethics Committee (Approval ID: 0120-99/2018/5, Project ID: L5-1845).

2.2. Experimental Setup

Starting twice from the left and twice from the right side, in randomized order, each skier performed four runs on a corridor-shaped slalom course with 20 gates placed symmetrically at 12-m intervals and with a displacement of 4 m (Figure 1). To ensure that this course was set precisely, the gates were positioned using the Leica Geodetic Global Satellite Navigation System (GNSS) 1200 with its built-in Stake-Out application (Leica Geosystems AG, Heerbrugg, Switzerland). The terrain selected had an average incline of 16°, with a maximal tilt to either side of <1°, and was groomed on each day of testing. In light of the hard, icy snow and temperatures between −2 and 0 °C, the coaches and experimental team smoothed the course prior to each and every run in an attempt to standardize conditions for side-skidding.

As described previously [24,25], three-dimensional whole-body kinematics were monitored utilizing the MVN Biomech V2018 inertial system (Xsens Technologies B.V., Enschede, The Netherlands) and Leica Zeno GG04 plus Real-Time Kinematics RTK GNSS (Leica Geosystems AG, Heerbrugg, Switzerland). The inertial system (calibrated twice prior to each run) was worn under the skier's racing suit and the smart antenna (RTK GNSS) was integrated into the back protector and positioned at shoulder height to allow unobstructed satellite reception (Figure 2). Data collected by the inertial system were recorded on a memory card, while data from the GNSS RTK system were transmitted wirelessly to a handheld device (Conker NS6, Conker, Takeley, England). In connection with each measurement, the precise position of the smart antenna relative to the thoracic (T12) and cervical vertebrae (C7) was determined to allow reliable integration of these two sets of data.

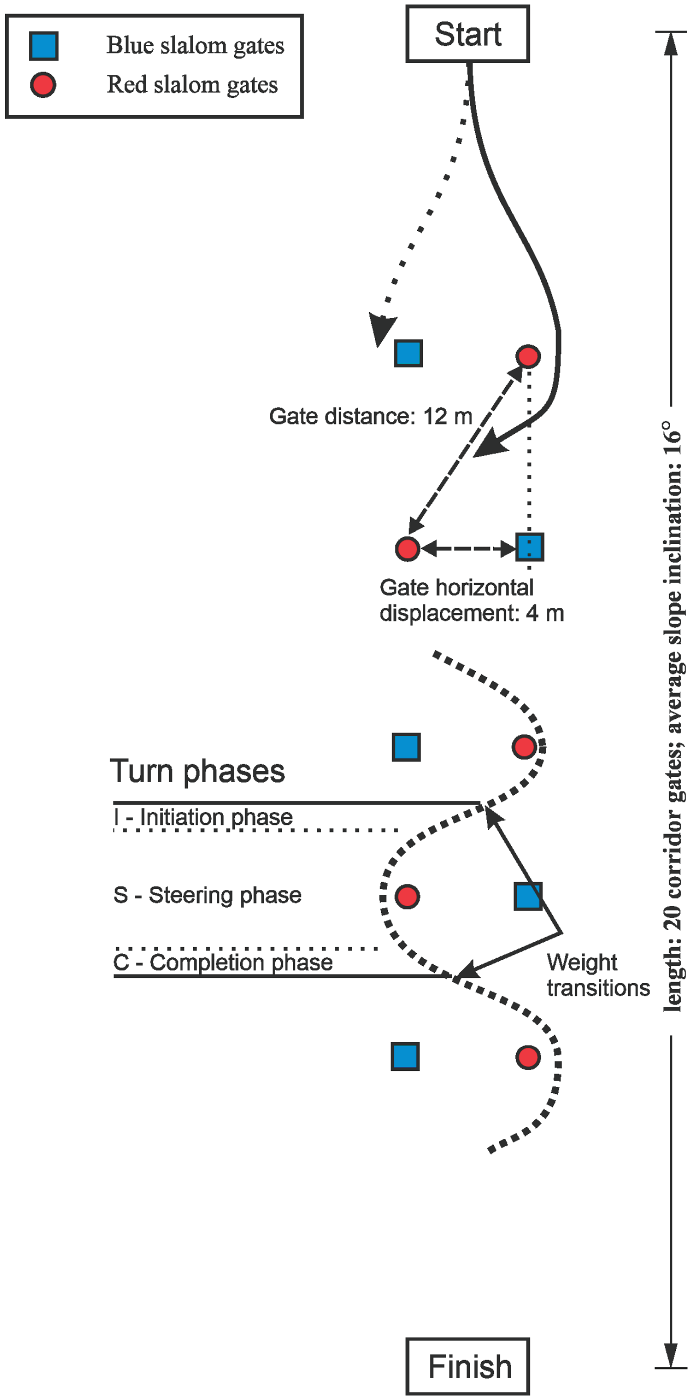

Figure 1. Schematic illustration of the corridor-shaped slalom course.

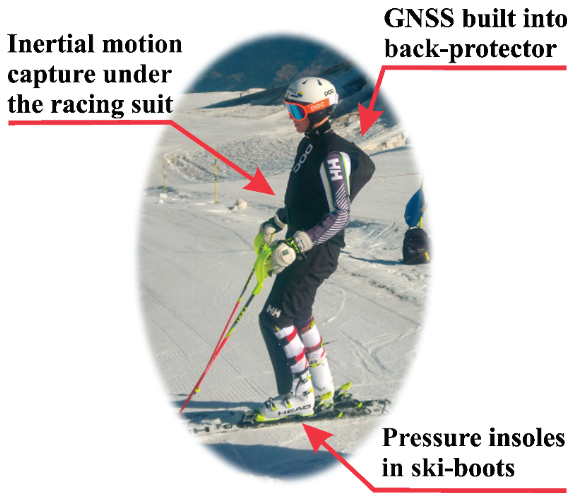

Figure 2. Equipment of the slalom skier with the global navigation satellite and inertial motion capture systems and pressure insoles.

In addition, the skier's boots were equipped with pressure insoles (Loadsol, Novel GmbH, Munich, Germany) that assessed the total ground reaction force acting perpendicular to the sole of the ski boot, the individual forces acting on the entire inside and outside foot and the distribution of force between the fore and rear foot. To assist analysis, all runs were also filmed at 50 Hz with a high-resolution camera (GC-PX100, The Japan Victor Company Ltd., Yokohama, Japan). To allow synchronization of all measurements, each skier performed three active squats and three hits with one of his skis on the ground before each start.

2.3. Computation

To match the frequency of the inertial system, the RTK GNSS system's captured trajectories at 20 Hz and the force measurements at 100 Hz were interpolated with cubic splines to 240 Hz. Following synchronization of the data collected by these three systems, these data were smoothed with the Rauch–Tung–Striebel algorithm [26], which utilizes a zero-lag two-way Kalman filter, in a manner similar to an earlier study [24]. The local coordinates provided by the inertial system were thereafter transformed into the global coordinates employed for RTK GNSS measurements by adding an extra node to the position of the RTK GNSS smart antenna. The data were subsequently transferred from Matlab R2016b (Mathworks, Natick, MA, USA) to the Visual 3D v6 software (C-Motion, Germantown, MD, USA), where the skier's center of mass (CoM) and the trajectory of the skis were calculated. The CoM was calculated utilizing Demster's regression equations [27], with inclusion of the mass of both the skiing and measuring equipment. The trajectory of the skis was defined as the arithmetic mean of the trajectories of the ankle joints [11].

The distance travelled and turn radius [7] were determined from the trajectory of the skis. From the trajectory of the CoM, the differential specific mechanical energy (i.e., the change in mechanical energy per unit change in altitude, normalized to the mass of the skier) [7] and mechanical energy for each specific section (normalized to the entrance speed) [5], which reflect instantaneous and sectional performance, respectively, were calculated. The definitions of both of these performance parameters mean that their values are negative when energy is dissipated. The flexion angles of the knee and hip joints on the left and right legs were provided directly by the inertial system. The angles of the inside and outside shanks, defined as the minimal tilt of the shank around the axis defined by the ski in relationship to the surface of the slope (Figure 3), were also calculated. Each turn was divided into initiation, steering and completion phases, as described previously [11] (Figure 1). To examine for temporal asymmetries, the left and right turning times were compared.

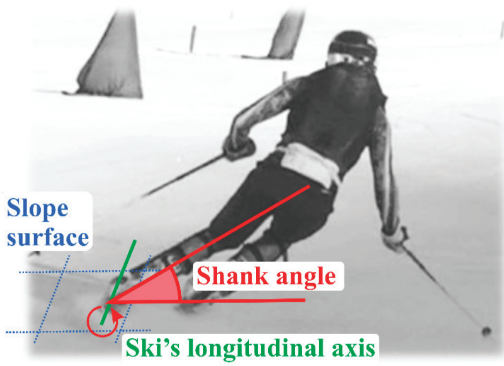

Figure 3. Photograph of a skier illustrating the angle of the shank.

Asymmetry between the left (L) and right (R) sides was expressed as the index SI = 1 − (|L − R|)/(L + R), where L and D represent the average values of parameters during the steering phase of the turn, with the exceptions of turn length, time, speed and sectional energy loss, which were determined for the entire turn. As an indicator of overall (as opposed to average) asymmetries throughout the entire turn, the Jaccard index (JI) [28] was also calculated. To obtain this index, the mean value and standard deviation of each parameter at each % of the turn were calculated. Then, the two curves obtained by adding or subtracting the standard deviation to the mean value were taken to represent the upper and lower boundaries, respectively, of the polygon delineating the turn. Thereafter, the overall JI was calculated as (A∩B)/(A∪B), where A and B represent the polygons associated with the left and right turns, respectively. In practice, when JI is equal to 1, the areas defined by the mean ± standard deviation boundaries for the left and right turns overlap entirely, whereas when JI is equal to zero, there is no overlap at all.

2.4. Statistical Analyses

All data are presented as mean values and standard deviations. The Shapiro–Wilk test was used to assess normality. Outliers detected employing standard Tukey's fences (1.5 interquartile range) were excluded from further analysis. A paired sample t-test was used for post hoc analysis of potential differences. In connection with the multivariable linear regression models, no more than two predictive (independent) variables were allowed. The dependent (predicted) variables were based on the objectives of the study related to performance (SI for turn time, turn length and average speed, and SI and JI for energy losses), while the independent (predictor) variables were related to skiing technique (SI and JI for the angles of flexion and inclination) and load (SI and JI for ground reaction forces). In connection with the multivariable linear regression models, no more than two predictive (independent) variables related to skiing technique (SI and JI for the angles of flexion and inclination) and load (SI and JI for ground reaction forces) were allowed, while the dependent (predicted) variables were related to performance (SI for turn time, turn length and average speed, and SI and JI for energy losses). All predictions in which G * Power (Faul et al., 2009, Heinrich University Heine Düsseldorf, Germany) was less than 0.8 were excluded. The level of statistical significance was set at $p < 0.05$. All statistical analyses were performed in the Matlab software.

3. Results

3.1. Descriptive Statistics, Symmetry and Jaccard Indices (SI and JI)

The descriptive statistics and symmetry indices for the independent variables (skiing technique and ground reaction forces) and dependent variables (skiing performance) during skiing are presented in Tables 1 and 2, respectively. In most cases, the differences in the independent variables during left and right turns were statistically insignificant (Table 1), the exception being GRF on the entire inside foot ($p < 0.05$). The mean symmetry indices (SI) for the independent variables related to skiing technique ranged from approximately 92 to 98%, with associated Jaccard indices (JI) during the steering phase ranging from approximately 29 to 53%. The corresponding values for the independent variables related to GRF ranged from approximately 85 to 98% and approximately 42 to 71%, respectively.

Table 1. The inclination, flexion of the joints and ground reaction forces (GRF) acting on various parts of the legs during the steering phase of left and right turns by elite slalom skiers, together with the corresponding symmetry (SI) and Jaccard (JI) indices (independent variables). All values presented are means ± standard deviations.

Variable	Left Turn	Right Turn	*p*-Value	SI [%]	JI [%]
Shank angle [°]					
Outside leg	30.8 ± 4.5	29.4 ± 4.6	0.49	93.8 ± 5.4	52.2 ± 19.5
Inside leg	33.2 ± 3.8	34.2 ± 2.4	0.84	92.8 ± 4.0	41.5 ± 16.2
Knee flexion [°]					
Outside leg	46.99 ± 8.9	52.20 ± 7.2	0.11	92.5 ± 4.4	28.7 ± 24.3
Inside leg	85.73 ± 9.3	81.25 ± 9.9	0.34	96.1 ± 2.2	39.1 ± 21.7
Hip flexion [°]					
Outside leg	37.4 ± 3.3	28.02 ± 3.0	0.70	95.71 ± 2.2	53.35 ± 14.9
Inside leg	71.8 ± 4.4	68.79 ± 5.5	0.22	97.52 ± 1.7	50.64 ± 15.5
GRF (pressure insoles) [% BW]					
On the entire foot					
Outside leg	126.2 ± 19.2	113.6 ± 21.6	0.21	92.9 ± 4.7	56.1 ± 18.9
Inside leg	66.8 ± 7.4	76.0 ± 10.0	0.04	91.4 ± 5.7	56.0 ± 19.6
On the fore foot [% BW]					
Outside leg	62.5 ± 20.6	58.7 ± 26.85	0.75	88.4 ± 8.4	47.2 ± 21.6
Inside leg	27.4 ± 9.2	37.8 ± 17.6	0.14	85.1 ± 10.1	42.7 ± 23.2
On the rear foot [% BW]					
Outside leg	63.8 ± 7.7	54.9 ± 16.6	0.17	87.8 ± 7.3	51.6 ± 14.4
Inside leg	39.4 ± 9.13	38.6 ± 15.8	0.85	85.8 ± 15.2	52.9 ± 23.2
GRF *					
Overall [% BW]	287.5 ± 26.3	283.7 ± 17.5	0.72	98.2 ± 1.1	71.3 ± 2.7

BW—body weight; SI—symmetry index; JI—Jaccard index; * approximated on the basis of the movement of the center of mass.

Moreover, none of the values for the dependent variables reflecting skiing performance differed significantly between the left and the right turns (Table 2). The mean SI for the dependent variables ranged from approximately 71% (in the case of instantaneous performance) to approximately 100% (average velocity). The nature of the parameters involved allowed the JI values to be calculated only for the turning radius and instantaneous performance during the steering phase as approximately 56% and 47%, respectively.

The patterns of the angle of the outside shank of all nine skiers during left and right turns, together with the corresponding JI during the steering phase (ranging from 14% for Skier I to 87% for Skier G), are shown in Figure 4. As depicted in the diagram, the mean angle of the outside shank during left and right turns differed during the entire steering phase for Skiers H and I, during the second half of the steering phase for Skiers B, D and E and during the first half of this phase in the case of Skier A. In contrast, the mean angle of the outside shank of Skier G was largely the same throughout the entire steering phase. With respect to the mean turning radius of left and right turns, most of the skiers demonstrated visible differences during the second half of the steering phase, with Skier G again being the exception (Figure 5). Moreover, the JI of 81% for the turning radius of Skier G was the largest observed, while the smallest JI of 56% in this regard was demonstrated by Skier C. Visually larger differences were observed between left and right turn instantaneous performance (Figure 6) with the JI ranging from 31% (Skier I) to 78% (Skier G).

Table 2. The time, trajectory, velocity and energy dissipation during left and right turns by elite slalom skiers, together with the corresponding symmetry (SI) and Jaccard indices (JI) (dependent variables). All values presented are means ± standard deviations.

Dependent Variable	Left Turn	Right Turn	*p*-Value	SI [%]	JI [%]
Time					
Turning time [s]	0.87 ± 0.03	0.87 ± 0.03	0.68	97.5 ± 1.7	*n*/a
Trajectory					
Turning length [m]	12.61 ± 0.30	12.51 ± 0.39	0.59	97.9 ± 1.5	*n*/a
Turningradius[m]	9.34 ± 0.44	9.32 ± 0.52	0.95	97.6 ± 1.5	56.1 ± 18.9
Velocity					
Average velocity [m/s]	14.5 ± 0.42	14.5 ± 0.37	0.97	99.6 ± 0.00	*n*/a
Energy associated with					
Instantaneous performance [J/kg/m]	−10.69 ± 4.67	−10.51 ± 2.98	0.92	70.6 ± 23.0	47.3 ± 14.1
Sectional performance [Js/kg/m]	−1.90 ± 0.39	−1.87 ± 0.50	0.91	84.2 ± 13.7	*n*/a

n/a—not applicable; SI—symmetry index; JI—Jaccard index.

3.2. Multivariable Regression Models

Altogether, our multivariable linear regression models, each involving no more than two predictor (independent) variables, included a total of 26 predictor and 8 predicted (dependent) variables. Models were discarded if the p-value was >0.05, $R^2 < 0.7$ or when the model's predictor coefficients did not differ significantly from 0 (t-statistic, $p < 0.05$). In addition, to restrict our analysis to results that could be meaningful, only the 13 models for which at least one of the predictor coefficient values was >0.1 are shown in Table 3. Of these, all included two independent variables, with the exception of Model #10, which only included one.

The largest predictor coefficients were associated with the SI values for instantaneous (differential specific mechanical energy) and sectional performance (mechanical energy for each specific section/turn normalized to the entrance speed) (Models #10–13, Table 3). The independent variables in Models #10 and 12 were related only to skiing technique, while those in Models #11 and 13 were related to skiing technique in combination with GRF. The remainder of the models had smaller predictive coefficients of 0.46 (Model #5) or lower, among which the coefficients for SI and JI for turning radius were largest (Models #4 and 5). Interestingly, the largest predictive coefficients obtained with Models #6–9, designed to predict the SI for average velocity, all corresponded to the SI for overall GRF.

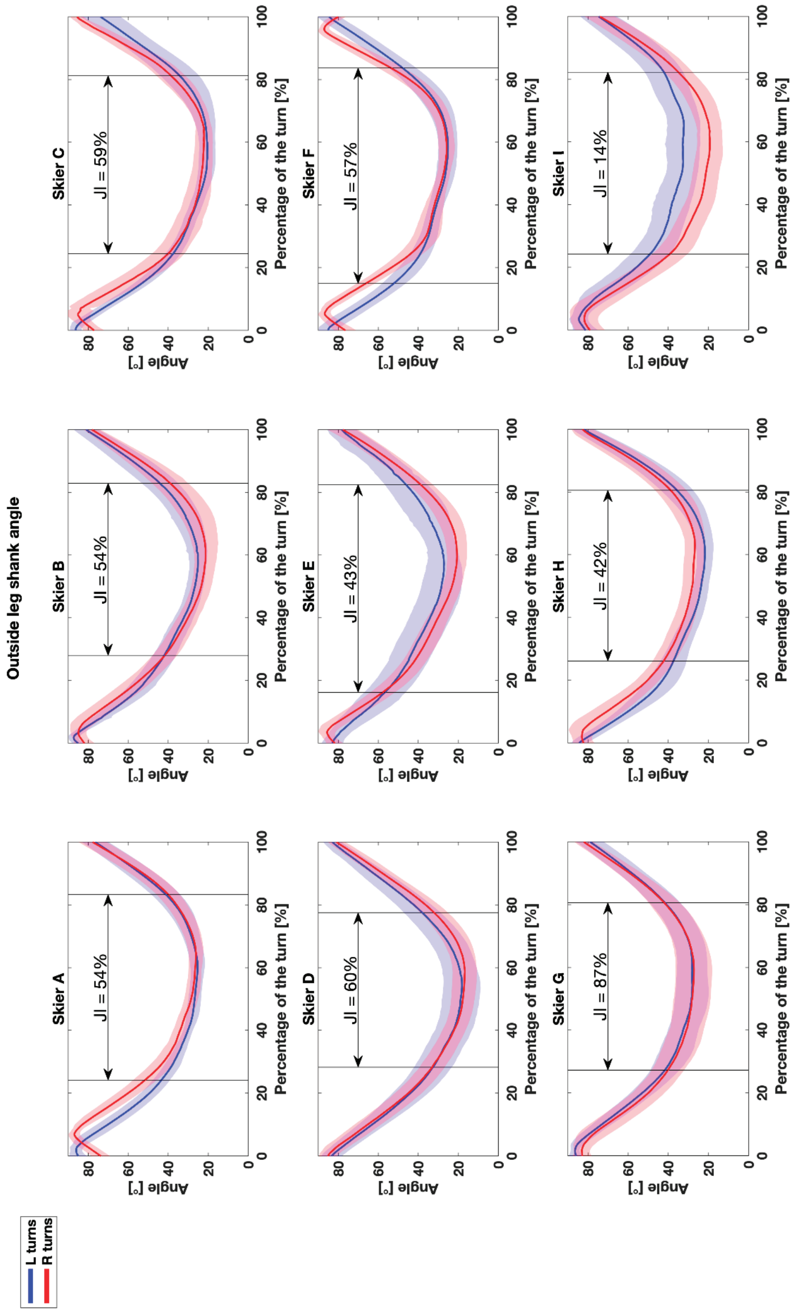

Figure 4. The angle of the outside shank of the 9 elite slalom skiers (**A**–**I**) during the steering phase of left and right turns, together with the corresponding Jaccard indices (JI). The two vertical lines indicate the beginning and end of the steering phase.

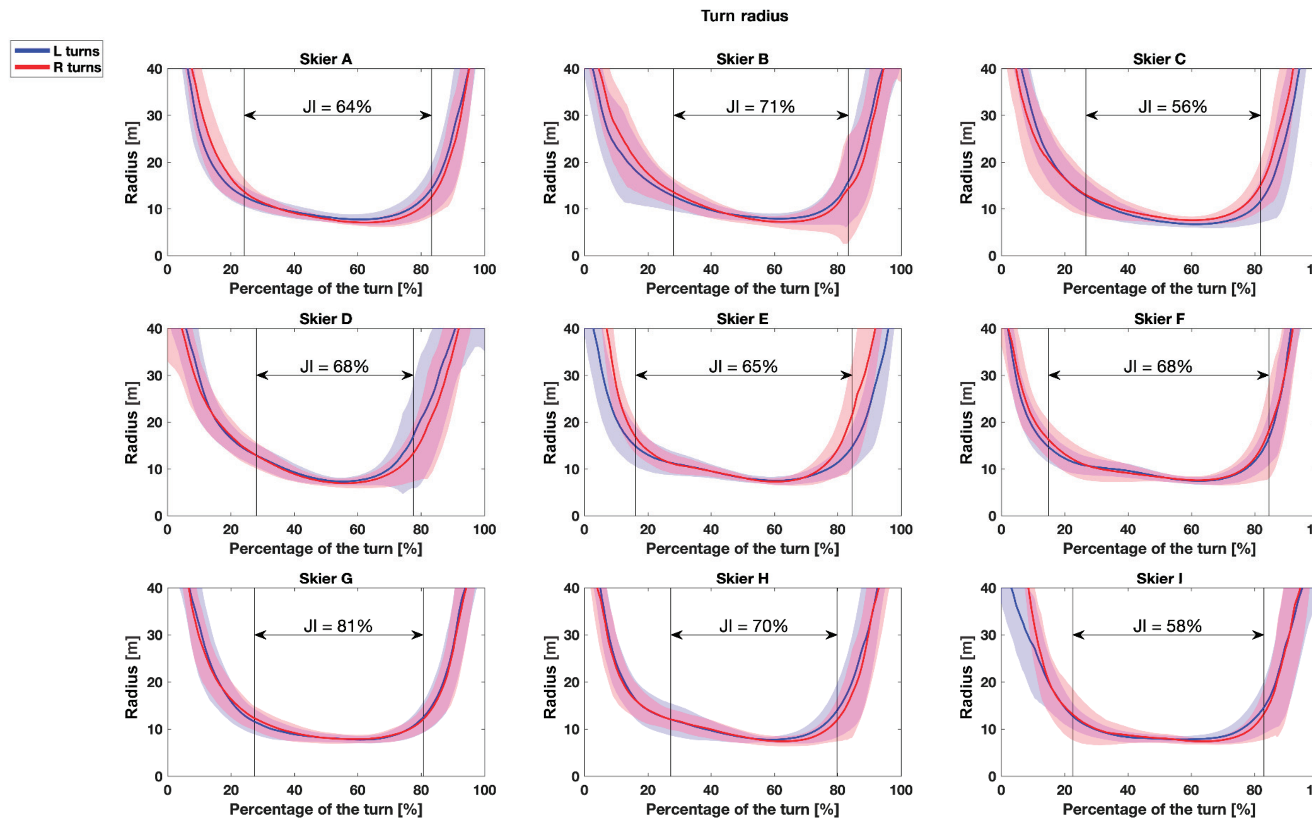

Figure 5. The turn radii during the steering phase of left and right turns by 9 elite slalom skiers (**A**–**I**) and corresponding Jaccard indices (JI). The two vertical lines indicate the beginning and end of the steering phase.

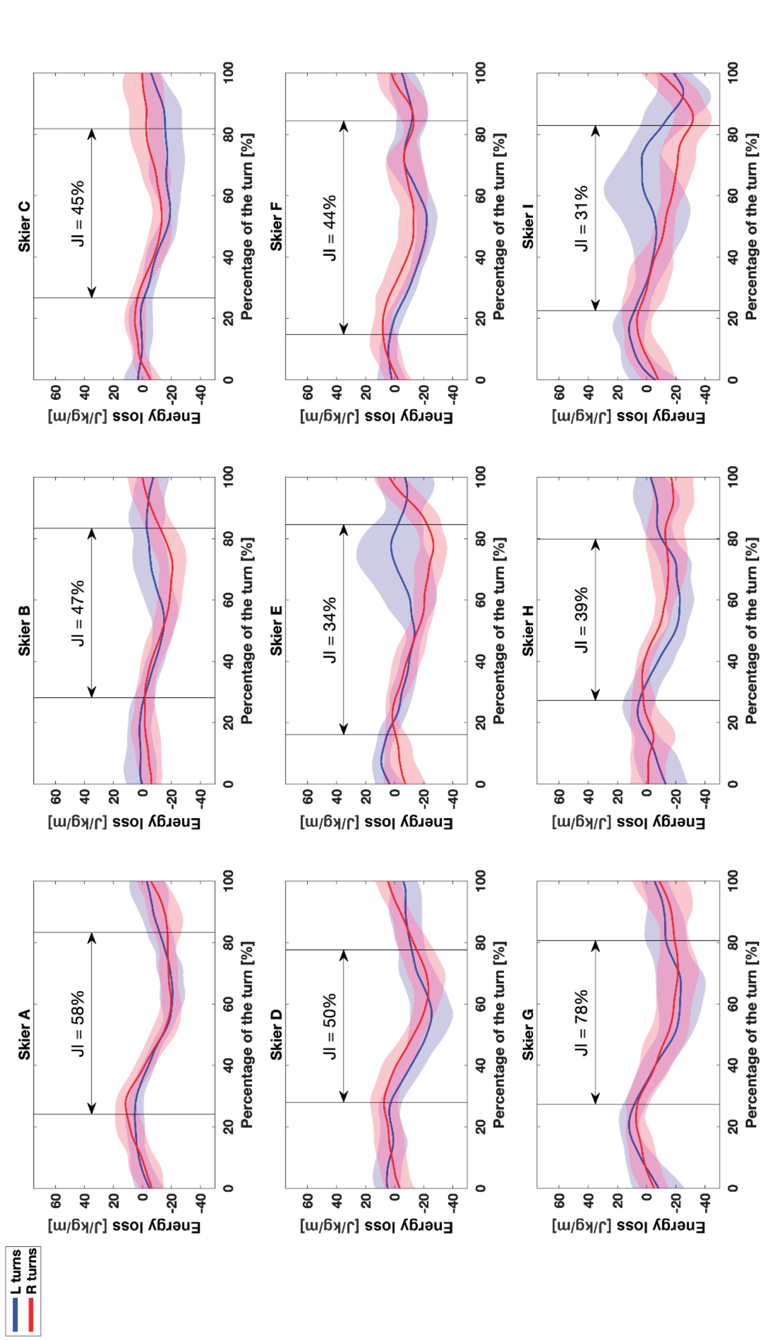

Figure 6. The instantaneous performance during the steering phase of left and right turns by 9 elite slalom skiers (**A–I**) and corresponding Jaccard indices (JI). The two vertical lines indicate the beginning and end of the steering phase. Instantaneous performance is defined as energy dissipation per change in altitude normalized relative to the mass of the skier and his equipment.

Table 3. Multivariable linear regression analysis of the relationships between the predicted (dependent, columns) and predictor (independent, rows) variables. The values in each column represent the coefficients of predictor variables.

Dependent Variables → Independent Variables ↓	SI for Turning Time	SI for Turning Length	JI for Turning *n* Radius	SI for Turning Radius	SI for Average Velocity	SI for Instantaneous Performance	SI for Sectional Performance
Shank angle							
JI for outside leg	-	-	0.33 $^{**,\#4}$	-	-	-	-
SI for outside leg	-	-	-	-	-	3.97 $^{***,\#10}$	3.01 $^{**,\#13}$
JI for inside leg	0.08 $^{*,\#1}$	0.07 $^{**,\#2}$	-	-	-	-	-
SI for inside leg	-	-	-	-	-	5.77 $^{**,\#11}$, 7.16 $^{**,\#12}$	-
Hip flexion							
JI for outside leg	-	-	-	−0.10 $^{*,\#5}$	0.01 $^{*,\#6}$	-	-
SI for outside leg	-	-	-	-	0.09 $^{*,\#7}$	8.33 $^{*,\#12}$	-
GRF on entire foot [a]							
JI for GRF outside leg	-	-	0.25 $^{*,\#4}$	-	-	-	-
SI for GRF outside leg	-	-	-	0.46 $^{**,\#5}$	-	-	-
SI for GRF inside leg	0.14 $^{*,\#1}$	0.13 $^{**,\#2}$, 0.11 $^{*,\#3}$	-	-	-	-	-
JI for GRF inside leg	-	-	-	-	-	-	0.56 $^{*,\#13}$
GRF on rear foot [a]							
JI for outside leg	-	-	-	-	−0.02 $^{**,\#8}$	−1.03 $^{**,\#11}$	-
SI for GRF outside leg	-	-	-	-	−0.03 $^{**,\#9}$	-	-
Overall GRF [b]							
JI	-	0.16 $^{*,\#3}$	-	-	-	-	-
SI	-	-	-	-	0.10 $^{*,\#6}$, 0.12 $^{**,\#7}$, 0.15 $^{**,\#8}$, 0.16 $^{**,\#9}$	-	-
R^2	0.72 $^{*,\#1}$	0.80 $^{**,\#2}$, 0.75 $^{*,\#3}$	0.80 $^{**,\#4}$	0.74 $^{*,\#5}$	0.73 $^{*,\#6}$, 0.81 $^{**,\#7}$, 0.84 $^{**,\#8}$, 0.83 $^{**,\#9}$	0.86 $^{***,\#10}$, 0.82 $^{**,\#11}$, 0.84 $^{**,\#12}$	0.76 $^{**,\#13}$

* —$p \leq 0.05$, ** —$p \leq 0.01$; *** —$p \leq 0.001$; # *n*—multivariable regression model number; GRF—ground reaction force; SI—symmetry index, JI—Jaccard index; [a] determined by pressure insoles; [b] approximated on the basis of the movements of the center of mass.

4. Discussion

The major novel finding here was confirmation of the hypothesis that asymmetries in technique and ground reaction forces are associated with asymmetries in the performance of elite, competitive slalom skiers. More specifically, (i) asymmetries in instantaneous and sectional performance were associated with the largest predictor coefficients for asymmetry in the angle of the shank and hip flexion on the outside leg; and (ii) asymmetry in turning radius demonstrated the largest predictor coefficients for asymmetry in the angle of the shank and GRF on the entire foot of the outside leg.

Our descriptive statistics showed that, on average, these elite alpine skiers performed left and right turns quite symmetrically (Tables 1 and 2), with the only statistically significant difference between these turns being the GRF on the entire foot of the inside leg. In particular, the average mean values for performance were almost identical for the left and right turns (Table 2). Furthermore, the symmetrical indices (SI) were all above 84% (sectional performance), except for instantaneous performance (70%).

This symmetry, which in light of the very small differences in performance of elite alpine skiers [9,29,30] was not unexpected, confirmed that our experimental setup was well suited for observing differences between left and right turns. Previously, the differences in the GRF and temporal parameters associated with left and right slalom turns by highly skilled ski instructors were also reported to be non-significant [23]. Similarly, the mean difference in strength between the dominant and non-dominant legs of elite Austrian alpine skiers was also small [31].

In the present case, the only SI that was markedly lower concerned instantaneous performance (70.6%). Overall, sectional and instantaneous performance demonstrated the most pronounced asymmetries, which was the initial rationale for employing these as measures of alpine skiing performance [5,7,30]. In giant slalom as well, utilization of energy-based performance over an entire section was found to be a valuable measure of performance [9].

However, the Jaccard indices (JI) revealed much more pronounced asymmetry between left and right turns, with the lowest value being only 28.6% (for flexion of the outside knee) and the highest 71.3% (for the overall GRF) (Table 1). The lowest individual JI value for the angle of the outside shank was only 14% (Skier I, Figure 4) and during the steering phase, a difference between left and right turns by this skier was clearly visible. This same skier exhibited the lowest JI for instantaneous performance (Figure 6) and the second lowest for turning radius (Figure 5). At the same time for Skier G, the largest JI for the angle of the outside shank (Figure 4) was associated with the largest JI values for both turning radius (Figure 5) and instantaneous performance (Figure 6). The dependence of sectional and instantaneous performance on the SI for the angles of both the inside and outside shank received further support from the multivariable regression analysis (Models #10–13, Table 3). Similarly, the JI for turning radius proved to be dependent on the corresponding value for the angle of the outside shank (Model #4, Table 3), an observation which in itself clearly demonstrates that asymmetry in technique is associated with asymmetry in performance. Such a relationship is not entirely unexpected, since according to the theory of carving skiing, the inclination of the ski is related to turning radius [32] and, moreover, in the case of slalom skiing, turning radius is related to instantaneous performance [5].

The SI for turning radius was not dependent on the SI for the angle of the outside shank. This independence demonstrates that the mean turn values taken into consideration when calculating SI did not take the profound turn cycle information into account as was the case with JI values in Model #4 (Table 3). The SI for turning radius was negatively correlated with the JI for flexion of the outside hip (predictor coefficient −0.10, Model #5, Table 3). This negative association means that less pronounced asymmetry in flexion of the outside hip should correspond to more asymmetry in the turning radius, an observation that we were unable to explain at present.

The predictor coefficients for JI and SI for the GRF acting on the entire foot of the outside leg were also relatively large in connection with the JI and SI for the turning radius (Models #4 and 5, Table 3). This finding can be explained by the action of radial forces, whose basic biomechanical modeling has shown to be dependent on the turning radius [32,33]. In this context, it is important to emphasize that only the GRF acting on the outside leg, not the overall GRF, was a predictor in the multivariable models. Indeed, in a previous study [5], this overall GRF did not differ between better and poorer slalom skiers. However, in the present investigation, the SI for average velocity was dependent on the corresponding value for the overall GRF in combination with several other "less important" variables with small predictor coefficients (Models #6–9, Table 3). This particularly interesting finding reveals that despite the virtually identical average velocity and overall GRF associated with left and right turns by our elite skiers, the asymmetries in these variables were actually large enough to demonstrate related dependency in the multivariable models (Tables 1 and 2).

The largest predictor coefficients observed in our multivariable models concerned the dependence of the SI for instantaneous performance on the combination of the SI values for the angle of the inside shank and flexion of the outside hip (Model #12, Table 3). The only apparent explanation for this dependency is the speculation that skiing technique influenced how smoothly the skis glide, (e.g., the attack angle defined as the angle between the longitudinal axis of the ski and the ski's center point's velocity vector projected onto a plane parallel to the surface of the snow) [14]) and/or the distribution of pressure under the ski and thereby the ski–snow interaction [34]. Either or both of these influences could exert an impact on energy dissipation.

Finally, some of the symmetry indices (SI) observed here, such as those for turning time, turn length and sectional performance, were dependent on various parameters related to the asymmetry of the inside leg (Models #1–3 and 13). This indicates that asymmetries in performance were also associated with the behavior of the inside leg, which has earlier been suggested to only play a role in maintaining stability while skiing [35]. Ski coaches already pay special attention to the inside leg in connection with training to optimize performance, but our findings provide the first experimental evidence that this is a valid concern.

Although the current investigation was extensive, assessing the full-body three-dimensional kinematics and GRF in connection with 720 slalom turns, like all studies, has certain limitations. Although some researchers question the reliability of inertial measurement systems and GNSS and/or pressure insoles, their reliability for in-field measurements on alpine skiers has already been demonstrated [23–25,35–39] and, moreover, we utilized state-of-the-art technology in this respect, i.e., one of the most up-to-date and accurate Leica Geosystems RTK GNSS systems and the latest version of the Xsens inertial motion capture hardware. However, since it was not possible to install an inertial sensor on a foot in a ski boot, we were unable to monitor flexion of the ankle joint. It would have been possible to measure bending of the ski boot, but this does not entirely reflect the more complicated three-dimensional behavior of the ankle joint (i.e., technique).

In addition, although GRF can certainly be measured most accurately with dynamometers/force-plates [40], the size and weight of these devices disturb the skiing equipment and, thereby, the performance of the skier. To avoid this, we used pressure insoles here, which do not always indicate the magnitude of GRF accurately [41]. On the other hand, direct measurement of the pressure on the soles, an important parameter when skiing [23,35], is especially useful for dealing with asymmetries in pressure on different parts of the foot. To assess a more precise magnitude of the GRF, we performed biomechanical modeling of this parameter based on the acceleration of the center of mass monitored by three-dimensional kinematics, as in our previous studies [11,42].

As is true of virtually all studies on alpine skiing, generalization of our present results, despite the relatively large size of our study population, is not straightforward. The snow, terrain and weather were nearly ideal during our testing and similar studies under varying conditions are now required.

5. Conclusions

In conclusion, the application of descriptive statistical analysis to left and right turns by elite slalom skiers revealed that with respect to technique, ground reaction forces and performance, these turns were quite symmetrical, with the only significant difference being related to the mean GRF on the entire inside foot. Furthermore, all symmetry indices for skiing technique and performance were >92%, with the exception of those for instantaneous (70.6%) and sectional performance (84.2%), demonstrating the relevance of these latter two parameters in connection with the analysis of skiing asymmetry. The Jaccard index, which takes into account behavior within the turn cycle, was found to be more sensitive to asymmetries than the symmetry index, which is based solely on the mean values of the parameters. Although the movements of elite slalom skiers were found to be quite symmetrical, this is the first demonstration that asymmetry in their skiing technique and ground reaction forces influences asymmetry in their performance. These findings constitute experimental support for the efforts of coaches to achieve symmetrical skiing technique, not only in order to decrease the risk of injury [31], but also to optimize overall performance.

Author Contributions: Conceptualization, M.S. and H.-C.H.; methodology, M.S. and J.O.; formal analysis, J.O. and M.S.; data collection and handling, M.S. and J.O.; writing—preparation of the first draft, M.S.; writing—review and editing, all authors; visualization, J.O. and M.S.; supervision, M.S.; project administration, M.S.; funding acquisition, H.-C.H. and N.Š. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The authors would like to sincerely thank all the skiers and their coaches for their helpful cooperation. Many thanks also to Alessandro Galloppini and Mads Kjær Madsen Mads for their help with the data collection and to Uwe Kersting for performing inertial motion capture.

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2

The Influence of Ski Waist-Width and Fatigue on Knee-Joint Stability and Skier's Balance

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Abstract: Alpine skiing is a complex sport that demands a high level of motor control and balance. In general, skiers are prone to deterioration in the state of fatigue due to using inappropriate equipment. As a consequence, the risk of injury might increase. This study aimed to examine the influence of fatigue and ski waist-width on knee-joint stability and skier's balance. A laboratory skiing simulation in a quasistatic ski-turning position was conducted where the lower-limb kinematics was recorded using an optical system, and the balance-determining parameters were captured using a force plate. It was demonstrated that the knee-joint kinematics and skier's balance were hampered in the state of fatigue, as well as when using skis with a large waist-width. The results of the study suggest avoiding the fatigue state and the use of skis having a large waist-width while skiing on hard surfaces to decrease the risk of injury.

Keywords: skiing simulation; optical motion capture; tensiometer; ski waist-width; balance; knee injury

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1. Introduction

Competitive alpine skiing is a physically demanding sport that requires a combination of strength, strength endurance, postural balance, and coordination [1,2]. It comprises a sequence of high-intensity isometric and concentric-eccentric contractions [3]. Recreational skiing is also considered a very intense activity, especially when viewing a recreational skier in terms of their physical abilities. In alpine skiing, the ground reaction force and, thus, the body load is the greatest in the steering phase of the turn after passing the fall line [4,5]. That is when the eccentric work of the muscles also occurs [3]. In competitive skiing, fatigue reduces the skiing speed, increases the turning radius [3], and debilitates the ability to maintain balance, which can result in a loss of skiing control, fall, or injury [6,7]. Indeed, alpine skiing is a sport with a high risk of injury, having an overall injury rate of approximately 2–4 injuries per 1000 skier-days in recreational skiing [8–10] and ~10 per 1000 runs in World Cup competitive skiing [11].

Fatigue may occur in the muscle itself (local or peripheral fatigue) and on the level of the nervous system (central fatigue). Local fatigue is related to the impaired transmission of an action potential, an impaired association between muscle stimulation and contraction, and inhibition of the contractile process [6], while central fatigue is connected to reduced initiation or transmission of motoneuron electrical activity [12]. The development of peripheral fatigue is progressive and depends on the duration of the activity and its intensity. Peripheral muscle fatigue is considered short-lived when it largely ends within 1 min, with phosphocreatine and strength recovery, and it is long-term when the effects of fatigue remain for at least 30 min after activity [13].

Static equilibrium is defined as the ability to maintain the center of mass (CoM) above the support surface [14]. When the center of pressure (CoP) of the ground reaction force is outside the support surface, the body loses balance or an appropriate human action (e.g., a step) occurs in order to maintain or restore equilibrium [15]. In upright standing, the body uses two main strategies to compensate for challenged balance. In anterior–posterior disturbances, an ankle strategy occurs in which most compensatory movements are performed by the ankle and foot [16]. In disturbances that act in the medial–lateral direction, the body responds with a hip strategy, in which more complex movements occur, especially in the hip joint and torso [16,17]. The contribution of the hip increases with a reduced support surface and with larger and faster disturbances. In skiing, the strategy of the ankle is not expressed because the ankle joint is in a stiff ski-boot and, therefore, does not possess much freedom of movement. Thus, the skier uses predominantly knee and hip joint movements to maintain balance and to regulate the angle of the ski against the snow, from which the turning radius is determined (and, consequently, radial forces) in connection with carved turns [18].

Recently, skis have appeared on the market that are much wider than ordinary skis in the part under the ski boot (waist-width above 100 mm compared to 60 mm on classic skis). Such skis were originally designed for skiing off-piste. However, current skis with waist-widths between 80 and 90 mm are considered “allride skis” for on- and off-piste skiing, consequently often being used on hard or icy snow. In powder (off-piste) skiing, such skis have a wider support base and better flow on the snow. When wide skis are being used on icy/hard snow conditions, the outside and more loaded ski’s point of application of the ground reaction force is farther away from the middle of the foot and shifted medially compared to when using narrower skis [19]. It was found that the knee-joint kinematics is consequently different on wider skis than on narrower ones, with knee rotation being more affected than knee abduction/adduction. In a study that simulated a quasi-static equilibrium position in a ski turn, it was found that the kinematic changes in the knee were such that the torque in the joint remained unchanged, regardless of the width of the ski [20]. The possible explanation for this was that, by keeping the external torques relatively low, there was also less muscle effort.

From studies analyzing human gait, it is known that, as the antigravity muscles get fatigued, the total speed of movement of the CoM, the amplitude of movement in the mediolateral and anteroposterior directions, and the total range of motion of the CoM increase [21,22]. The purpose of the current research was to investigate the functional stability of the knee joint and balance in a quasi-static simulation of a ski turn when using skis of different waist-widths in connection with fatigue, as the lower-limb muscle fatigue might be an injury risk factor in skiing [23]. In a broader context, the study examined hitherto unknown factors that could affect knee-joint injury, which was proven to be the most commonly injured joint in both recreational and competitive skiing [24,25].

The following hypotheses were set:

Hypotheses H1a. *Fatigue causes a statistically significant increase in external tibial rotation and knee abduction/valgus compared to prefatigue values.*

Hypotheses H1b. *The fatigue-induced change in the position of the knee joint (external rotation and abduction/valgus of the knee) is statistically significantly more pronounced in connection with wider skis compared to narrower ones.*

Hypotheses H2a. *Fatigue results in a statistically significant increase in the movement of the center of pressure on the ground (CoP) compared to prefatigue values.*

Hypotheses H2b. *The fatigue-induced increase in the movement of the CoP is statistically significantly more pronounced with wider skis compared to narrower ones and, consequently, the body balance and the knee-joint stability in the fatigue state are hampered more when using wide skis compared to narrow ones.*

2. Materials and Methods

Fifteen healthy male participants were included in the study (age 33.4 ± 8.6 years; height: 176.9 ± 7.9 cm; weight: 77.3 ± 13.2 kg). They were all physically fit and they were all skiers. None of them had any injury in the last year and no serious injury of any body part at any time in their life span. The study was approved by the responsible Ethics Committee at the University of Ljubljana (No. 1327/2017) and informed consent following the Declaration of Helsinki was obtained from all subjects.

2.1. Measurement System

For three-dimensional photogrammetry, 11 reflective optical markers were placed in accordance with a standardized protocol [26]: six on the outer lower limb, two on the ski boot, and three on the movable plate of the simulator (Figure 1). The reflective markers were recorded using an optical kinematic system (Optitrack V120: Trio, Natural Point, USA), consisting of three calibrated infrared cameras (sampling rate: 120 Hz). With the manufacturer's software (Motive, version 1.5.0.), we obtained real-time information on the position of body segments and standard Euler's angles in the knee joint in three anatomical planes [27].

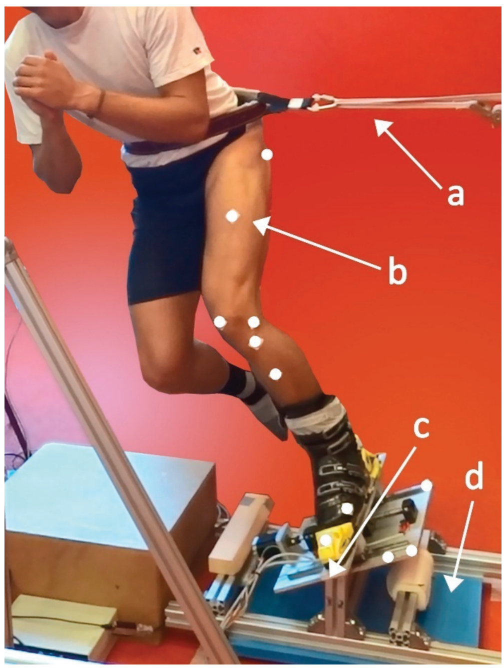

Figure 1. A ski turn simulator with a participant: (**a**) lateral supporting strap with pressure/tensile force gauge; (**b**) optical marker; (**c**) axis of rotation; (**d**) force plate.

The same ski simulator as in a previous study [20] consisted of a metal plate that was attached to the frame such that the plate could be tilted around the sagittal axis (Figure 1). With the help of three optical markers mounted on the simulator's plate, the ski-binding-boot (lower shell of the ski boot) coordinate system was determined. This coordinate system was used to calculate the Euler angles in the knee joint (flexion–abduction–rotation). The ski binding for fastening the ski boot moved freely in the plane of the plate transverse to the axis of rotation with the help of a stepper electric motor controlled by a computer. The ski waist-width was simulated by the displacement of the ski-binding-boot from the axis of rotation (imaginary ski-edge) as shown in Figure 2. The starting position, i.e., ski width = 0, was defined when the mid-sole of the ski-boot was aligned with the axis of rotation (nonrealistic ski width) and, thereafter, two realistic waist widths were simulated: narrow ski = 60 mm and wide ski = 120 mm.

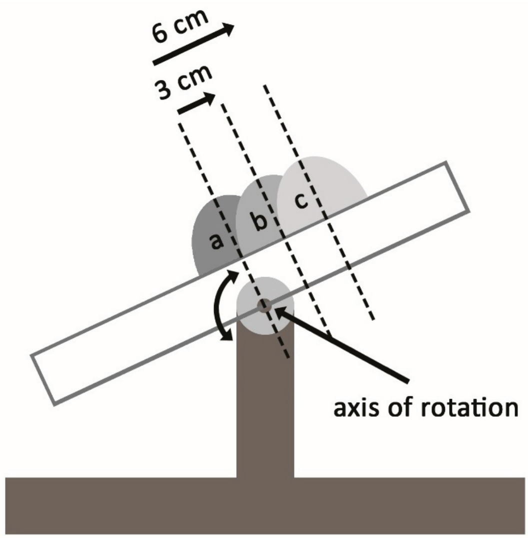

Figure 2. A frontal-plane schematic of the apparatus that enabled simulating different ski waist-widths. The elliptic shapes represent the left/outside ski-boot in the simulated right ski-turn. The axis of rotation (pointed by the arrow) represents the inner edge of the left (outside) ski. The simulated width of the ski is equal to the doubled distance between the axis of the rotation (ski edge) and the mid of the boot. The positions "b" and "c" simulated the 60 and 120 mm ski waist-widths, respectively. The position "a" is nonrealistic and was used only to collect reference values. The computer-guided electromotor (not shown on the schema) moved the platform with the ski-boot-binding system between the presented positions.

The participant was strapped to the side via a pressure/tensile force gauge (HBM model: S9M/2 kN, Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany). The force gauge was connected to an analog-to-digital converter (DEWE 43, Dewesoft d.o.o., Trbovlje, Slovenia). With the help of the Dewesoft X program and the appropriate length of the rope, it was initially ensured that the radial force always represented approximately the same proportion of the force of gravity and, thus, the angle of inclination of the entire body was quasi-statically determined.

Data on the magnitude and direction of the ground reaction force were captured using the Kistler 5691 force plate (Kistler, Winterthur, Switzerland) on which the ski simulator was placed and the accompanying Kistler MARS software (Kistler, Winterthur, Switzerland).

2.2. Measurement Protocol

The subject was bonded to a robotic ski simulator with his left ski-boot, while the other ski-boot was lifted from the ground throughout the measurement (simulation as if all the weight is on one leg during the turn). The computer-controlled system randomly changed the position of the ground reaction force four times every 10 s, simulating three ski waist-widths: 0 mm (used as a reference value), 60 mm ("narrow ski"), and 120 mm ("wide ski"). The subject had to maintain 60° of flexion in the knee joint and 25° inclination of the plate for 10 s after each ski-width change on the simulator. These predefined values of knee flexion and ski inclination were set to avoid other influences on knee kinematics and to focus only on ski width, as well as to enable a skiing-like body position and ground reaction forces [20]. Both knee flexion and ski inclination conditions were monitored in real time using on-screen visual feedback. Sets lasting 40 s were repeated three times with a 2 min resting interval. This was followed by a fatigue protocol, during which the subject performed three series of one-legged squats in a ski-boot to a knee flexion angle of 70°. The knee angle during squats was monitored on the screen in real time by the participant. The participants were loudly encouraged to perform the squats until failure, i.e., until no additional squat could be performed, which enabled us to meet one of the most common definitions of muscle fatigue: "the exercise-induced decrease in the ability to produce force" [28]. During each series of squats, the subject had 30 s of rest. The fatigue phase was followed by three additional 40 s random "waist-width" load sequences on the simulator: the first immediately after fatigue, the second 2 min after fatigue, and the third 4 min after fatigue.

2.3. Data Processing

For each 10 s measurement on the simulator under different simulated waist-widths, data from the last 5 s before the new waist-width position occurred were used. Thus, the subject had sufficient time for each simulated waist-width to occupy a quasi-static balanced position.

From the kinematics system, flexion, abduction, and rotation in the knee joint [27] were obtained. The force transducer enabled monitoring the magnitude of the radial force in the simulated turn. From the force plate, the following data were obtained:

1. CoP velocity, defined as the common length of the trajectory of the CoP sway calculated as a sum of the point-to-point Euclidian distance divided by the measurement time (total velocity; V_{tot}), or the total length of the trajectory of the CoP sway only in the anteroposterior (V_{AP}) or mediolateral (V_{ML}) direction, divided by the measurement time.
2. CoP amplitude, defined as the average amount of the CoP sway in anteroposterior (A_{AP}) and mediolateral (A_{ML}) direction, calculated as the total length of the trajectory of the CoP sway only in the given direction divided by the number of changes.
3. CoP area (AR), defined as the area swayed by the CoP trajectory with respect to the central stance point (i.e., a product of mean anteroposterior and mediolateral values).

The mean frequency (MF) of the power spectrum of CoP in both directions (anteroposterior: MF_{AP}, mediolateral: MF_{ML}), defined as the frequency of the oscillations of the CoP calculated as the mean frequency of the power spectrum in a given direction. The peak frequency (PF) of the power spectrum of motion CoP in both directions (anteroposterior: PF_{AP}, mediolateral: PF_{ML}), calculated as the peak frequency of the power spectrum in a given direction.

Frequency was calculated as CoP changes in a direction (i.e., signal local extremes or peaks) divided by the measurement time (FP) for both directions (anteroposterior: $FP_{AP,}$ mediolateral: FP_{ML}).

First, the baseline value of the parameters was determined by calculating the average of the first three measurements for all CoP parameters at a reference waist-width of 0 mm. In the next step, these CoP prefatigue reference values were compared with the values obtained immediately after fatigue, 2 min after fatigue, and 4 min after fatigue on simulated skis of different widths.

2.4. Statistical Analysis

SPSS.20 (IBM Corporation, New York, NY, USA) and MS Excel 2013 were used for statistical analysis. Data were presented as mean and standard deviation.

The normality of the distribution was first tested using Kolmogorov–Smirnov test and then the homogeneity of variances was tested using the Leven test. Analysis of variance for repeated measurements was used to test the differences between the dependent variables. In the post hoc analysis, the difference between individual pairs was tested with paired-sample *t*-tests.

A two-way analysis of variance for repeated measurements (measurement time (4) × ski waist-width (3)) was used to determine whether there were statistically significant differences in parameters at the measurement time factor (before fatigue, immediately after fatigue, 2 min after fatigue, and 4 min after fatigue), with the ski waist-width factor (neutral, narrow, and wide) and with the interaction of both factors (measurement time × ski waist-width). To separately determine whether the groups differ from each other, in terms of ski waist-width (narrow vs. wide ski) and in terms of measurement time, a one-way analysis of variance was performed. Effect sizes were calculated as η2 for variance analysis, as well as for pairwise comparisons using the Cohen's *d* measure [29]. The level of statistical significance was determined at $p < 0.05$.

3. Results

The knee flexion angle was predetermined and monitored in real time for all measurements on the ski simulator, and the results revealed that there were no statistically significant differences in knee flexion parameters. There were also no statistically significant differences in knee rotation parameters, whether with the ski waist-width parameter or with time before or after fatigue (Figure 3).

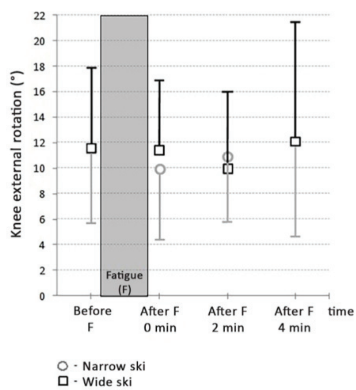

Figure 3. External tibial rotation in a prefatigued state (before F) and at different times after fatigue (after F) with two different ski waist-widths.

The knee abduction was significantly larger in connection with the wide skis (Figure 4) compared to the narrow ones ($t = -5.1$; $p < 0.01$; $d = 0.46$).

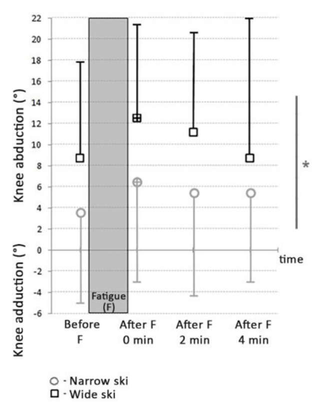

Figure 4. Knee abduction/adduction in a prefatigued state (before F) and at different times after fatigue (after F) with two different ski waist-widths. + depicts statistically significant difference compared to prefatigued state ($p < 0.05$); * depicts statistically significant difference between all-narrow against all-wide waist-width measurements.

After fatigue, there was significant increase in knee abduction with narrow skis ($t = -2.16$; $p = 0.05$; $d = 0.31$), as well as with the wide ones ($t = -2.39$; $p < 0.05$; $d = 0.41$).

Significant differences were observed in V_{AP} with wide skis compared to narrow ones ($F = 3.78$; $p < 0.05$; $\eta^2 = 0.27$) (Figure 5).

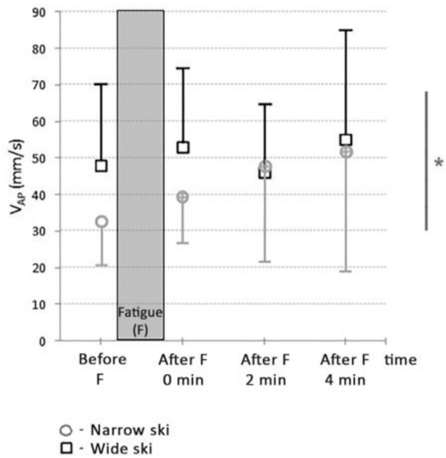

Figure 5. Center of pressure (CoP) velocity in anteroposterior direction (V_{AP}) in a prefatigued state (before F) and at different times after fatigue (after F) with two different ski waist-widths. + depicts statistically significant difference compared to prefatigued state ($p < 0.05$); * depicts statistically significant difference between all-narrow against all-wide waist-width measurements.

The V_{AP} value for wide skis was significantly higher compared to that for narrow ones ($t = -3.44$; $p < 0.01$; $d = 0.52$). With narrow skis, all three after fatigue V_{AP} values were significantly higher compared to the prefatigue value with the immediate after fatigue value being the highest ($t = -2.70$; $p < 0.05$; $d = 0.42$).

There were significantly higher V_{ML} values with wide skis ($F = 19.94$; $p < 0.01$; $\eta^2 = 0.67$) compared to narrow ones ($t = -4.87$; $p < 0.01$; $d = 0.70$) (Figure 6).

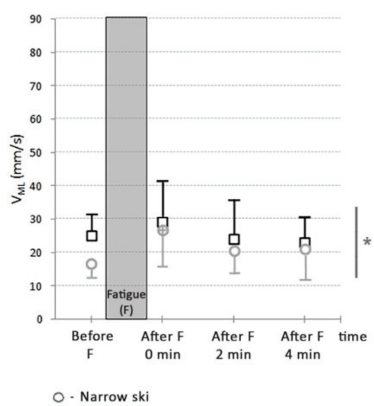

Figure 6. CoP velocity in mediolateral direction (V_{ML}) in a prefatigued state (before F) and at different times after fatigue (after F) with two different ski waist-widths. + depicts statistically significant difference compared to prefatigued state ($p < 0.05$); * depicts statistically significant difference between all-narrow against all-wide waist-width measurements.

The effect of time was statistically significant for narrow skis only ($F = 4.42$; $p < 0.01$; $\eta^2 = 0.29$). Specifically, there was an increment in V_{ML} immediately after fatigue compared to the prefatigue state with narrow skis ($t = -3.73$; $p < 0.01$; $d = 0.56$).

The results demonstrated significant differences in A_{ap} values between different ski widths ($F = 4.89$; $p < 0.05$; $\eta^2 = 0.31$) (Figure 7).

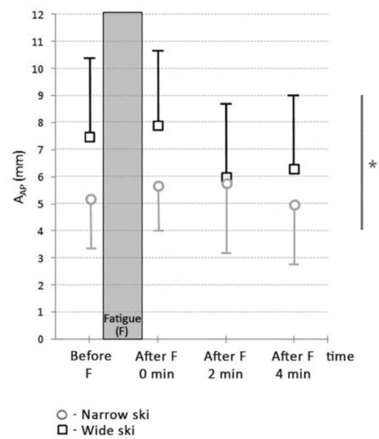

Figure 7. CoP amplitude in anteroposterior direction (A_{AP}) in a prefatigued state (before F) and at different times after fatigue (after F) with two different ski waist-widths. * depicts statistically significant difference between all-narrow against all-wide waist-width measurements.

The A_{AP} values were significantly higher with wide skis compared to narrow ones ($t = 2.23$; $p < 0.05$; $d = 0.31$). The differences between pre and after fatigue times were significant with wide skis only ($F = 4.28$; $p < 0.05$; $\eta^2 = 0.28$). There was a decrement in A_{AP} value 2 min after fatigue compared to the state immediately after fatigue ($t = 2.92$; $p < 0.05$; $d = 0.38$).

There were significant differences in A_{ML} values between different ski widths ($F = 20.36$; $p < 0.01$; $\eta^2 = 0.63$). The A_{ML} values were significantly higher with wide skis compared to narrow ones ($t = -5.18$; $p < 0.01$; $d = 0.69$) (Figure 8).

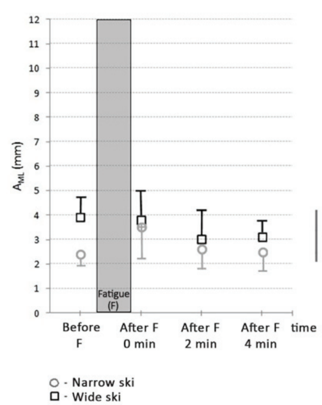

Figure 8. CoP amplitude in mediolateral direction (A_{ML}) in a prefatigued state (before F) and at different times after fatigue (after F) with two different ski waist-widths. + depicts statistically significant difference compared to prefatigued state ($p < 0.05$); * depicts statistically significant difference between all-narrow against all-wide waist-width measurements.

The effect of time of measurement was statistically significant for narrow skis only (F = 5.00; $p < 0.01$; $\eta^2 = 0.31$) and A_{ML} was significantly higher only immediately after fatigue ($t = -3.44$; $p < 0.01$; $d = 0.52$).

Significant differences were observed in MF_{AP} with different ski widths (F = 5.93; $p < 0.01$; $\eta^2 = 0.37$). The MF_{AP} value was significantly lower with wide skis compared to the narrow ones ($t = 2.86$; $p < 0.05$; $d = 0.43$) (Figure 9).

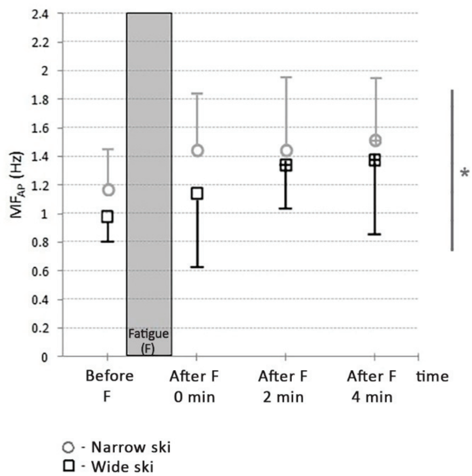

Figure 9. The mean frequency of the power spectrum of CoP in the anteroposterior direction (MF_{AP}) in a prefatigued state (before F) and at different times after fatiguing (after F) with two different ski waist-widths. + depicts statistically significant difference compared to prefatigued state ($p < 0.05$); * depicts statistically significant difference between all-narrow against all-wide waist-width measurements.

The differences between different times of measurement were significant with wide skis only (F = 3.38; $p < 0.05$; $\eta^2 = 0.30$) and MF_{AP} was significantly higher 2 min after fatiguing compared to the prefatigue value ($t = -4.17$; $p < 0.01$; $d = 0.66$), as well as 4 min after fatigue compared to the prefatigue value ($t = -3.32$; $p < 0.01$; $d = 0.50$). With narrow skis, there was a significant increment in MF_{AP} value only at 4 min after fatigue compared to the prefatigue value ($t = -3.5$; $p < 0.01$; $d = 0.53$).

There were significant differences in MF_{ML} values with time of measurement (F = 3.96; $p < 0.05$; $\eta^2 = 0.36$), as well as with different ski widths (F = 3.70; $p < 0.05$; $\eta^2 = 0.35$) (Figure 10).

MF_{ML} was significantly lower with wide skis compared to narrow ones ($t = 2.33$; $p < 0.05$; $d = 0.31$). With narrow skis, there was a significant increment in MF_{ML} values 4 min after fatigue compared to the prefatigue state ($t = -3.85$; $p < 0.01$; $d = 0.55$), as well as 4 min after fatigue compared to immediately after fatigue ($t = -2.73$; $p < 0.05$; $d = 0.40$). With wide skis, there was significant difference in MF_{ML} value only 4 min after fatigue compared to values 2 min after fatigue ($t = -2.33$; $p < 0.05$; $d = 0.31$).

With AR values, there were significant differences with different times of measurement (F = 5.36; $p < 0.01$; $\eta^2 = 0.52$), as well as with different ski widths (F = 4.33; $p < 0.05$; $\eta^2 = 0.46$). There were significantly higher AR values with wide skis compared to narrow ones ($t = -3.67$; $p < 0.01$; $d = 0.53$). With respect to different measurement times, there were significant differences in AR value with narrow skis only (F = 5.58; $p < 0.01$; $\eta^2 = 0.34$) with all the after fatigue values being significantly higher compared to the prefatigue state.

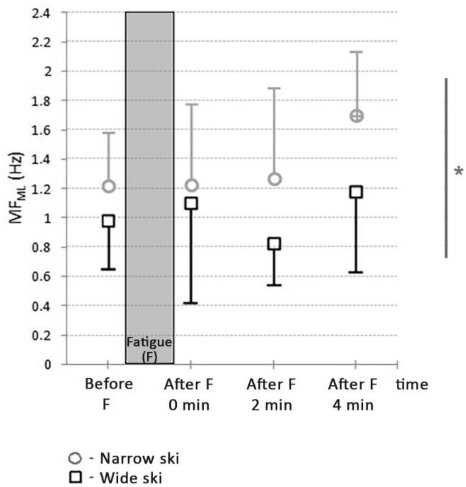

Figure 10. The mean frequency of the power spectrum of CoP in the mediolateral direction (MF_{ML}) in a prefatigued state (before F) and at different times after fatigue (after F) with two different ski waist-widths. + depicts statistically significant difference compared to prefatigued state ($p < 0.05$); * depicts statistically significant difference between all-narrow against all-wide waist-width measurements.

4. Discussion

The main findings of the study were, firstly, that knee joint stability (kinematics) was affected by the waist-width of the ski, as well as by the level of fatigue. Secondly, hypotheses H1a and H1b were only partly confirmed as only knee abduction increased with the ski waist-width and with the level of fatigue but not the knee rotation. Concerning the comparison of the functional stability in the simulated skiing position using different ski waist-widths, it was demonstrated that the fatigue caused a significant deterioration in knee stability with wide skis compared to narrow ones. Thirdly, fatigue resulted in an increase in CoP movement compared to prefatigue values, confirming hypothesis H2a. The fatigue effect on balance deterioration was significantly more influential with narrow skis compared to wide ones. Thus, hypothesis H2b was not confirmed. With most CoP parameters, it was shown that the effect of fatigue on balance was in accordance with previous studies [21,22,30].

Previous on-snow [19] and laboratory [20] studies demonstrated that knee rotation was the primary adaptation mechanism to avoid an increase in knee-joint torque when using wide skis. The knee abduction was independent of the ski waist-width [20]. In the present investigation, where the muscular fatigue effect was studied, knee abduction increased in the fatigue state with both ski widths, while rotation remained unchanged or there was even a trend of diminishing external rotation. One possible explanation is that, in a state of fatigue, abduction took on the role of minimizing torque in the knee joint instead of external rotation in combination with flexion, as found in a previous study. However, the knee-joint abduction that presently occurred imposes an additional strain on the medial collateral ligament [31]. The stiffness of this ligament is increased by lower-limb muscle activation [32], which is considered as an additional mediolateral knee stabilizer. This additional active stabilization mechanism could be hampered in the state of muscle fatigue. Thus, the knee abducted/valgus position becomes more pronounced and nearer to the ligamentous limitation of the end range of the knee valgus position, which might represent the risk of acute medial collateral injury in the case of additional sudden external valgus thrust [31], which may occur during skiing.

It is known from other biomechanical studies that knee-joint malalignment predisposes the knee joint to degenerative changes [33] via the local overload of joint surfaces. In our study, it was shown that, in the state of fatigue, and even more so in connection with wide skis, the knee is forced to the pronounced valgus position in the simulated ski turn. It can be assumed that, in such cases, the lateral knee compartment might be notably more loaded or, in the worst case, even overloaded. Nevertheless, knowing that ground reaction forces in recreational skiing are as high as two body weights [34] and in competitive skiing as high as 4.2 body weights [4,5], in combination with vibrations [35–37], this may increase the risk of chronic joint conditions. This especially applies to competitive and advanced recreational skiers/ski instructors because of their high number of ski runs/turns per season.

With most CoP movement parameters, the fatigue effect was most significantly expressed immediately after the fatigue procedure, in accordance with a previous study conducted on an isokinetic dynamometer [12]. Some of the parameters (V_{AP}, MF_{AP}, MF_{ML} with narrow ski, and MF_{AP} with wide ski) did not return to baseline even at the time of the last measurement (4 min after fatigue). Therefore, typical short breaks along the descent appear not to be sufficient to level out fatigue effects. These results in terms of skiing safety put into question long chair lifts or gondolas when skiers are not taking long enough breaks during their descents. In other studies that investigated the fatigue effect on the deterioration of muscle force production [12,38] and CoP movement [30], most of the force-producing functions and the balance returned to normal after 6 to 10 min. Such longer resting periods typically only occur in alpine skiing between runs, waiting for lifts, and travelling (back) up the mountain/slope. Nevertheless, previous studies reported that the body sway increased proportionally to the developing fatigue when the subjects ran on a treadmill [39]. In contrast, Bryanton and Bilodeau [40] observed that CoP movement started to increase with but plateaued or possibly even decreased during their fatigue protocol, consisting of a sit–stand exercise. It remains unknown how repeated bouts of high-intensity skiing throughout the training session/skiing day affect postural control. For future research, the effect of additional repetitive fatiguing should be examined to elucidate what is expected to happen with postural stability on a typical skiing day consisting of several consecutive runs.

The main limitation of this study was probably that it simulated skiing and was not conducted during on-snow skiing. On the other hand, in this way, the experiment was significantly more controlled. Moreover, forceful fatigue, applied in this study, would most likely pose a high risk of injury during experiments if it were to be performed in real skiing. Undoubtedly, such measurements should be performed in situations to minimize the risk of injury, and this was provided by the fatigue and skiing simulation in the laboratory. Future research incorporating less forceful (to decrease the risk of injury during the experiment) but repetitive fatigue followed by a resting period would further elucidate the effects of real skiing fatigue on balance and knee-joint stability.

5. Conclusions

The present study showed that the knee joint adapted to the fatigue state with an increase in knee abduction/valgus, with the effect being stronger with wide skis. Furthermore, the balance also deteriorated with fatigue using either ski width. The balance-hampering effect was more pronounced with the narrow skis. However, the stability parameters that were shown to be worse even before fatigue in connection with the wide skis compared to the narrow ones further deteriorated in the fatigue state and remained worse compared to the narrow skis throughout all after fatigue experiments. The study elucidates the fact that fatigue is an injury risk factor in skiing [6,7] from an additional point of view and exposes the further risk of using skis with a large waist-width, especially on hard frozen surfaces, as simulated in the study. Considering fatigue and ski waist-width related to balance deterioration, it is obvious that the injury risk for the whole body and not only the knee joint can be compromised. More specifically, the possible mechanisms of acute and chronic knee-joint injury were suggested. The medial collateral ligament tension and the uneven joint pressure distribution while turning in the fatigue state are potential biomechanical injury risk factors. Consequently, apart from using skis with a narrower waist-width, it might also be suggested to regularly interrupt “long” skiing runs/descents with long enough breaks to decrease the risk of injury.

Author Contributions: Conceptualization, M.S. and N.Š.; methodology, K.H.; formal analysis, K.H.; resources, M.S. and N.Š.; data curation, K.H. and M.Z.; writing—original draft preparation, M.Z. and K.H.; writing—review and editing, M.S., N.Š., and M.Z; visualization, M.Z. and M.S.; supervision, M.S. and N.Š.; project administration, N.Š. and M.S.; funding acquisition, N.Š. and M.S. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The authors would like to sincerely thank all participants for their involvement, as well as Bojan Nemec, Zlatko Matjačič, and Andrej Olenšek for development of the skiing simulator.

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3

Elbow Extensors and Volar Flexors Strength Capacity and Its Relation to Shooting Performance in Basketball Players—A Pilot Study

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Abstract: Rate of force/torque development scaling factor (RFD-SF/RTD-SF) has been used as a tool for assessing neuromuscular quickness. The aim was to investigate strength capacities of two major shooting muscle groups and their relationship to basketball shooting performance, and to compare the RFD-SF as well as shooting performance between junior and senior basketball players, and finally to examine the differences in RTD-SF between elbow extensors and volar flexors. In 23 male basketball players (13 juniors and 10 seniors) we assessed maximal isometric torque (T_{MVC}), maximal rate of torque development and RTD-SF slope ($k_{RTD\text{-}SF}$) for elbow extensors and volar flexors. The subjects performed 10 throws at 2.3 m (short) and 8.9 m (long) from the basket. Our results showed similar $k_{RTD\text{-}SF}$ and T_{MVC} in both groups. Better shooting performance from short distance was observed in senior players. Significant associations between $k_{RTD\text{-}SF}$, T_{MVC} and shooting performance were found only in juniors. Elbow extensors T_{MVC} was found to have a significant positive large association with shooting performance from long distance. It seems that muscle capacity has an important role in shooting performance in junior compared to players. Sufficient strength capacity of major shooting muscles is important for juniors' shooting performance from a long distance.

Keywords: wrist; elbow; shot; accuracy; RFD-SF

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1. Introduction

Rate of force development scaling factor (RFD-SF) has been used to quantify the ability to generate force rapidly, which is described as neuromuscular quickness [1]. A large number of studies have reported the RFD-SF as a reliable method for a number of muscle groups such as index finger abductors [1,2], elbow extensors [1,3], knee extensors [1,4] and various hip muscles [5]. However, the relationship between RFD-SF and performance in functional or sports-related tasks has not been yet investigated. It is known that muscle quickness decreases with age [2] or disease [6], while the influence of the specific training history on this ability is still, to a great extent, unknown.

Explosive and quick release during basketball shot is important to avoid the defender reaction. One of the studies showed positive effects of explosive strength training on the shot percentage level. However, explosive strength training was performed for upper and lower limb; therefore, it is unknown if upper limb strength capacities play important role in basketball shooting performance [7]. We speculate that upper limb strength capacities may be important for accurate shooting performance because it has been reported that an increase in maximum strength of elbow extensors positively affected the shoot accurately in the three-point shot [8].

Basketball shot is among the sports-specific movements in which rapid production of submaximal force by muscles that act across multiple arm joints is considered important. During a basketball throw, the players manipulate their shoulder, elbow, and wrist to generate the optimal ball speed and angular velocity of the joint at the time of the release [9], depending on the distance and the position from the basket. The angular velocity of the upper arm joints and the speed of ball release increase with the shooting distance [10], which suggests that higher submaximal involvement of the major muscle groups is required as the distance increases. The elbow extensors have been suggested as major contributors to release speed in basketball shooting [11,12] as they extend the elbow joint before release, while the activation of the volar flexors is an important component of shooting that optimises impulse applied to the ball at release [13]. Previous studies have reported that the angular velocity of the elbow joint of the shooting arm at release increases with distance from the basket, while the opposite is observed for the wrist [11], suggesting that the roles of the two joints vary with the shooting distance. Some earlier studies reported that players with more training experience had better shooting performance [12,14] and lower average duration of arm muscle activation [15,16]. Based on this, we assumed that junior and senior players might also differ in the neuromuscular quickness of the major shooting muscles (i.e., elbow extensors and volar flexors). Furthermore, the relationship between neuromuscular quickness and performance of sport-specific tasks has not yet been investigated. Filling these missing gaps could contribute to better understanding of RFD-SF and its use during routine testing of the athletes and possibly, based on these assessments, to individualized guidance of training programmes (e.g., more emphasis on speed-power training for individuals with lower RTD or RTD-SF).

To contribute our part in clarification of the functional role of the RTD-SF in sport-specific performance, we conducted a study to investigate strength capacities of elbow extensors and volar flexors in two groups of basketball players (juniors and seniors) and their relationship to shooting performance, put into the sport-specific training history. Specifically, the first aim of our study was to investigate the differences in the strength capacities (RTD-SF slope ($k_{RTD\text{-}SF}$), maximum torque (T_{MVC}), and peak rate of torque development (RTD_{PEAK}) of elbow extensors (EE) and volar flexors (VF) and the shooting performance between junior and senior basketball players. We hypothesised that senior players, based on their longer training history and complete physical development, have significantly higher strength capacities of elbow extensors and volar flexors and better shooting performance compared to junior players. The second aim of the study was to investigate the relationship between the strength capacities ($k_{RTD\text{-}SF,}$ T_{MVC}, and RTD_{PEAK}) and shooting performance. We hypothesised that in both groups, shooting performance would be significantly positively associated with $k_{RTD\text{-}SF}$, T_{MVC}, and RTD_{PEAK} of elbow extensors and volar flexors, at least from the long shooting distance. The third aim of the study was to investigate associations of elbow extensors and volar flexors as previous studies showed positive associations of $k_{RTD\text{-}SF}$ ability for different muscle groups, while this association between elbow extensors and volar flexors has not yet been confirmed. We hypothesised that there will be a large and statistically significant association in $k_{RTD\text{-}SF}$ between elbow extensors and volar flexors in both groups of players, which might support the idea of a central regulation and upper extremity (not a single joint, i.e., muscle group) related characteristics of RTD-SF ability.

2. Materials and Methods

2.1. Subjects

A total of 23 male basketball players from the top-ranked Slovenian basketball club were included in the study (Table 1). All subjects reported their right arm as the preferred shooting arm. Subjects with previous upper limb injuries (past 6 months), neurological disorders, low back pain, or recent general illness were excluded from the study. The inclusion criteria were regular basketball training in past 3 years at least 4 times per week. The subjects and their parents/guardians were informed about the testing procedures and provided written informed consent prior to commencing the study.

The experiment was approved by the Slovenian Medical Ethics Committee (approval no. 0120-99/2018/5) according to the Declaration of Helsinki.

Table 1. Characteristics of Subjects.

Group	N	Age (years)	Body Height (cm)	Body Mass (kg)	BMI	Training History (Years)
Junior	13	16.5 ± 0.9	192.7 ± 7.8	81.5 ± 9.1	21.9 ± 2.0	5.5 ± 1.8
Senior	10	24.0 ± 4.2	198 ± 7.9	95.5 ± 10.9	24.2 ± 1.6	14.1 ± 3.8
Total	23	19.7 ± 4.8	195.2 ± 8.2	87.6 ± 11.9	22.9 ± 2.1	9.3 ± 5.2

N—the number of participants; BMI—Body mass index.

2.2. Study Design and Testing Procedures

For each subject, we captured measurements of (i) $k_{RTD\text{-}SF}$, T_{MVC}, and RTD_{PEAK} for EE and VF of the self-reported preferred arm and (ii) shooting performance at two different distances from the basket in two separate visits. On the first measurement day, the subjects performed isometric strength tests for EE and VF (random order) preceded by a 10 min warm-up consisting of 5 min of light running, 4 min of dynamic stretching, and 1 min of activation exercises (10 repetitions of squats, push-ups, and V-ups). The isometric strength tests were performed before their regular training in the laboratory setting. The next day, on the second measurement day, the subjects performed 10 throws at two different distances (random order) from the basket after the standardized warm-up protocol described before. The shooting performance was assessed in the gym basketball gym before their regular training. The flowchart of the study is outlined on the Figure 1.

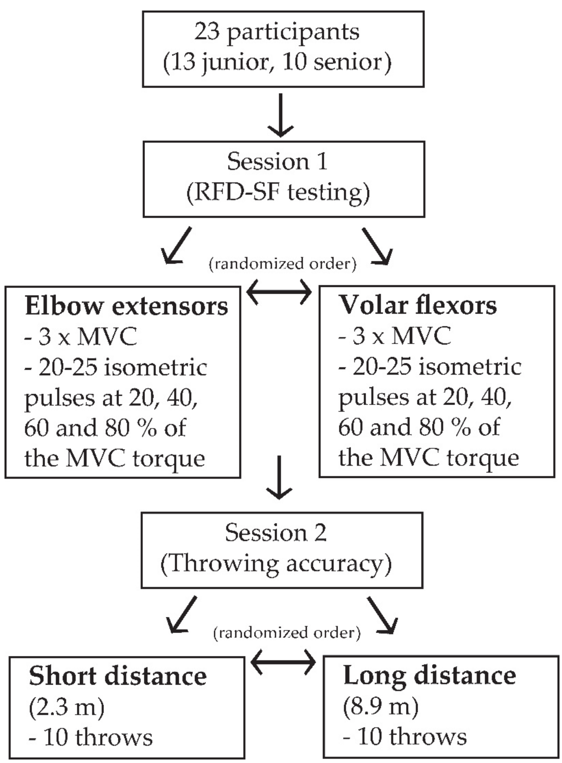

Figure 1. The flowchart of the measurement protocols. MVC—maximal voluntary isometric contraction.

Following the warm-up, the subject was positioned in a custom-made dynamometer (S2P, Science to Practice, ltd., Ljubljana, Slovenia) which was used for T_{MVC} and RTD_{PEAK} and $k_{RTD\text{-}SF}$ assessment. Participants position during elbow extension or volar flexion T_{MVC}, RTD_{PEAK}, and $k_{RTD\text{-}SF}$ assessment is presented and described in Figure 2. In all cases, the lever arm (i.e., the linear distance from the axis of the joint and the centre of the distal force-detecting support) was measured and considered in the torque calculation. The signals from force transducers during elbow extension (Bending beam load cell 1-Z6FC3/200kg, HBM, Darmstadt, Germany) and volar flexion (Tension compression load cell FL25-50 kg, Forsentek, Shenzhen, China) were amplified (Isotel, Logatec, Slovenia) and converted from analogue to digital signal (NI USB-6211, National Instruments, Austin, TX, USA). Signals were sampled at 1000 Hz by a custom-made LabView 2015 software (National Instruments Corp., Augustin, TX, USA). In case of T_{MVC} and RTD_{PEAK}, the raw signals were smoothed (moving average filter, 5 ms time-window). In RTD-SF analyses the signals were filtered using a lowpass Butterworth filter with cut-off frequency at 5 Hz, while corresponding RTD of each contraction was calculated as a peak value of derivate of the torque curve [4]. All measurements were processed by a single investigator.

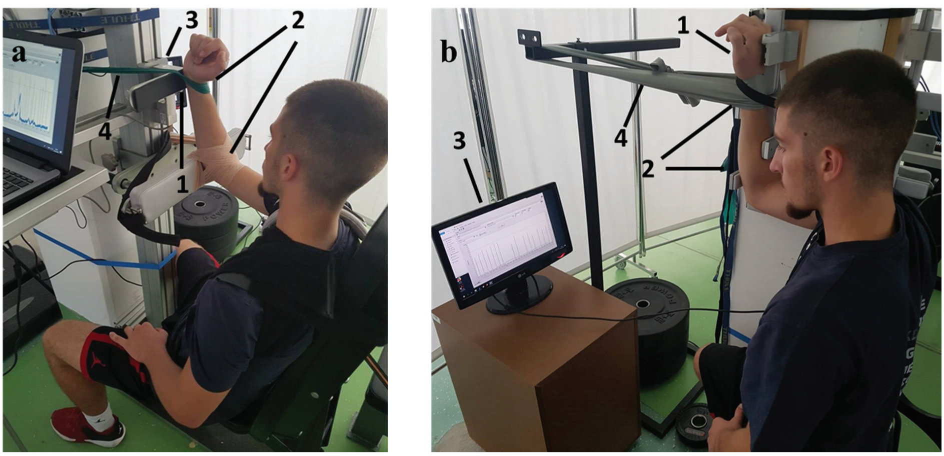

Figure 2. Measurement set-up: (**a**) Subject in the custom-built elbow extensor dynamometer. Subjects were seated (knee and hip in 90° position, trunk in upright position) on a bench with back support, while their shoulder and elbow were flexed at 90° in sagittal plane (forearm was in neutral position). The trunk and the shoulder of the performing arm were fixed to the back support, while the elbow was fixated to the lower support of the dynamometer. The force sensor was at the upper support, where the subject placed the wrist, which was fixated using elastic bands (to provide tension and proper contact between wrist and dynamometer support). (**b**) Subject in the custom-built volar flexor dynamometer. Subjects were seated on a chair. The subject's shoulder and elbow were both flexed at 90°, while their forearm (pronated position) was placed in a custom-made dynamometer which allows full forearm fixation. Wrist was in neutral position. 1—force sensor, 2—joint fixations, 3—monitor for visual feedback, 4—elastic band

2.3. Testing T_{MVC} and RTD_{PEAK}

In T_{MVC} testing subjects were instructed to gradually increase the force and push as hard as possible against the elbow (Figure 2a) and wrist dynamometer's support (Figure 2b). Contractions were sustained for at least 3 s; meanwhile, verbal encouragement was given to the subject. T_{MVC} for each muscle group was calculated (Nm/kg) as the maximal mean value on a 1 s time interval. Each participant performed three repetitions for each muscle group. The greatest T_{MVC} was used for statistical analysis.

Three isometric MVCs for each muscle group (EE and VF) with a 60 s rest between trials were repeated, while in this case subjects were instructed to push as hard and explosive as possible to calculate their RTD_{PEAK} (maximum of the toque-time derivative). Greatest RTD_{PEAK} (Nm/kg s) was used for statistical analysis.

2.4. Testing RTD-SF

The RTD-SF relationship for each muscle group was computed from sets of 20–25 explosive isometric contractions at four different submaximal intensities (20%, 40%, 60%, and 80% of T_{MVC}) (Figure 3a,c) in a random order, as previously described [1]. Subjects rested for 60 s between different contraction intensities and 3 min between each task, i.e., muscle group. The target torque was displayed as a horizontal line on a graph on a computer screen placed at the subject's eye level (Figure 2). The subjects were instructed to contract and relax as fast as possible.

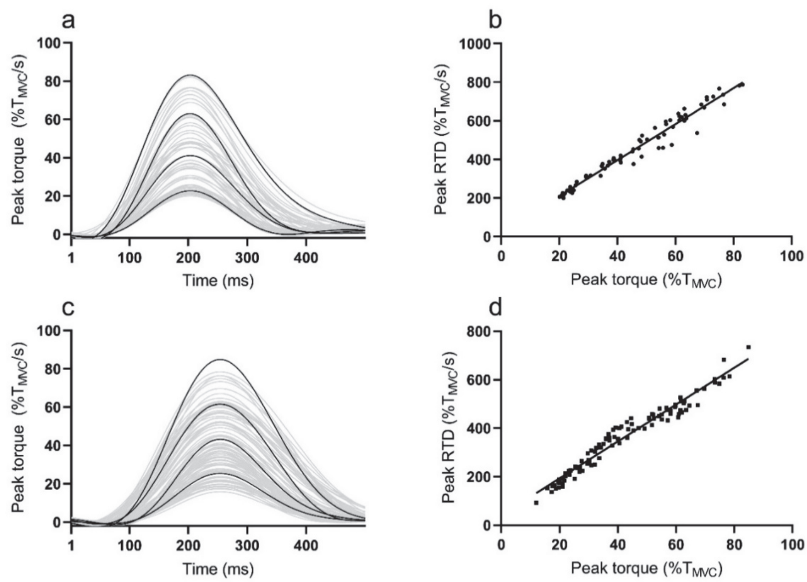

Figure 3. Sample recording of rapid torque pulses of (**a**) elbow extensors and (**c**) volar flexors to a variety of amplitudes. Rate of torque development scaling factor (RTD-SF) plot of (**b**) elbow extensors (**b**) and (**d**) volar flexors with data points taken from the peaks of the preferred arm.

The regression parameters $k_{RTD\text{-}SF}$ (/s) and $r^2_{RTD\text{-}SF}$ were obtained from the relationship between the peak torque and the corresponding peak RTD.

2.5. Testing Shooting Performance

During the second visit, the subjects performed 10 throws at two different distances, orientated frontally towards the basket. Shooting distances were selected in random order for each subject. Shooting performance from short distance was performed from half the distance between the basket and free throw line (2.3 m), while shooting form the longer distance was performed from 8.9 m (three-point line + distance between free throw and three-point line). From each subject shooting performance from each distance was assessed (n/10).

2.6. Statistical Analysis

Descriptive data of the dependent variables are presented as means and standard deviations. The Shapiro–Wilk test was used to assess data normality. Fisher's z-transformation was used to transform $r^2_{RTD\text{-}SF}$ in case of RTD-SF to obtain normal distribution. The differences in $k_{RTD\text{-}SF}$, T_{MVC}, and RTD_{PEAK} between groups were evaluated with a two-tailed independent sample t-test and Cohen's d effect size (ES). The ES was interpreted as negligible (<0.2), small (0.2–0.5), moderate (0.5–0.8), and large (≥0.8) [17]. Pearson correlation coefficients were used to determine the relationship between $k_{RTD\text{-}SF}$, T_{MVC}, and RTD_{PEAK} of EE and VF and shooting performance from short and long distance. The correlation coefficient was interpreted in as (0.00–0.19 trivial; 0.10–0.29 small; 0.30–0.49 moderate; 0.50–0.69 large; 0.70–0.89 very large; 0.90–0.99 nearly perfect; and 1.00 perfect) [18]. Moreover, we assessed the reliability of $k_{RTD\text{-}SF}$, T_{MVC}, and RTD_{PEAK} by calculating two-way random model intra-class correlation coefficients (ICC) for single measures and standard error of measurement, expressed as the coefficient of variation (CV). For T_{MVC} and RTD_{PEAK}, we conducted inter-repetition reliability, while for the RFD-SF, we split the data from each intensity into two halves, and compared $k_{RTD\text{-}SF}$ $r^2_{RTD\text{-}SF}$ obtained from both subsets of the data. The level of statistical significance was set at $p < 0.05$. Statistical analyses were performed using the SPSS (IBM SPSS version 26.0, Chicago, IL, USA) software package.

3. Results

The reliability of the outcome variables is shown in Table 2. For both muscle groups RTD-SF and T_{MVC} showed very good reliability (all ICC ≥ 0.85; all CV ≤ 5.66%); however, the reliability was somewhat lower for $RTD_{PEAK,}$ especially for the VF muscles (ICC = 0.54; CV = 15.21%).

Table 2. Reliability of the outcome variables.

Muscle Group/Variable		ICC	CV
Elbow extensors	T_{MVC}	0.91 (0.85–0.96)	2.34 (1.02–3.49)
	RTD_{PEAK}	0.78 (0.55–0.92)	7.89 (3.44–12.75)
	$k_{RFD\text{-}SF}$	0.99 (0.97–1.00)	1.23 (0.97–2.03)
	$r^2_{RFD\text{-}SF}$	0.88 (0.76–0.96)	1.05 (0.54–1.61)
Volar flexors	T_{MVC}	0.85 (0.72–0.94)	5.66 (2.81–8.44)
	RTD_{PEAK}	0.54 (0.23–0.84)	15.211 (8.76–21.12)
	$k_{RFD\text{-}SF}$	0.99 (0.96–1.00)	1.71 (1.11–2.58)
	$r^2_{RFD\text{-}SF}$	0.87 (0.67–0.96)	5.45 (2.36–9.21)

$k_{RTD\text{-}SF}$—slope of regression line, $r^2_{RTD\text{-}SF}$—linearity of regression line, T_{MVC}—maximal torque normalized on body weight, RTD_{PEAK}—maximal rate of torque development normalized on body weight.

Junior players had a significantly lower average number of training years (5.5 ± 1.8 years) compared to senior players (14.1 ± 3.8 years) ($t_{(21)} = −7.2$, $p < 0.013$). There was no statistically significant difference in height between groups ($t_{(21)} = −1.6$, $p = 0.11$), while senior players had statistically significantly higher body mass ($t_{(21)} = −3.4$, $p = 0.003$) and body mass index (BMI)($t_{(21)} = −3.0$, $p = 0.007$). Average $k_{RTD\text{-}SF}$, T_{MVC}, and RTD_{PEAK} values of elbow extensors and volar flexors in junior and senior group are presented in Table 3. Junior and senior players had similar values of T_{MVC} in both muscle groups, while junior players had significantly greater RTD_{PEAK} of EE and VF ($p = 0.003$–0.005, ES = 0.35–0.36). For both groups, a strong linear relationship ($r^2_{RTD\text{-}SF} = 0.93$–$0.95$) between the peak force and the RFD across submaximal contractions was calculated for both muscle groups (sample recordings are presented in Figure 3). There was no statistically significant difference in $k_{RTD\text{-}SF}$ between junior and senior players for elbow extensors or volar flexors. There was no difference in shooting performance from long distance, whereas senior players were more successful from short distance.

Table 3. Descriptive statistics and differences in measured parameters between junior and senior basketball players.

Muscle Group/Variable		Junior	Senior	t	p	ES
Elbow extensors	$k_{RTD\text{-}SF}$ (/s)	8.9 ± 0.9	8.5 ± 1.2	0.46	0.65	0.009
	$r^2_{RTD\text{-}SF}$	0.95 ± 0.04	0.93 ± 0.07	0.98	0.34	0.04
	T_{MVC} (Nm/kg)	0.70 ± 0.13	0.74 ± 0.16	−0.65	0.6	0.01
	RTD_{PEAK} (Nm/kg s)	9.9 ± 0.9	8.3 ± 1.3	3.45	0.005	0.36
Volar flexors	$k_{RTD\text{-}SF}$ (/s)	7.5 ± 1.0	7.3 ± 1.8	0.87	0.39	0.04
	$r^2_{RTD\text{-}SF}$	0.93 ± 0.04	0.94 ± 0.05	−0.35	0.73	0.006
	T_{MVC} (Nm)	0.21 ± 0.07	0.23 ± 0.03	−0.5	0.63	0.02
	RTD_{PEAK} (Nm/kg s)	9.2 ± 1.5	7.2 ± 1.3	3.3	0.003	0.35
Shooting performance	Short distance (%)	8.6 ± 1.2	10.0 ± 0.0	−3.9	0.02	0.56
	Long distance (%)	4.8 ± 2.2	6.3 ± 2.1	−1.7	0.1	0.12

$k_{RTD\text{-}SF}$—slope of regression line, $r^2_{RTD\text{-}SF}$—linearity of regression line, T_{MVC}—maximal torque normalized on body weight, RTD_{PEAK}—maximal rate of torque development normalized on body weight, Short distance—shooting distance at 2.3 m from the basket, Long distance—shooting distance at 8.9 m from the basket.

Significant associations between $k_{RTD\text{-}SF}$, T_{MVC}, RTD_{PEAK} (EE and VF) with shooting performance for junior players are presented in Figure 4. We calculated a large positive association between $k_{RTD\text{-}SF}$ of EE and VF and shooting performance from short distance (Figure 4a,b), while significant negative large associations were seen between $k_{RTD\text{-}SF}$ of both muscle groups and shooting performance from long distance (Figure 4c,d). Moreover, a significant positive large association was calculated between T_{MVC} of EE and shooting performance from long distance (Figure 4e), while the association between T_{MVC} of VF and shooting performance was not statistically significant (Figure 4f). No statistically significant associations were calculated in junior players between RTD_{PEAK} of both muscle groups and shooting performance (r = 0.246–0.315, p = 0.48–0.49). There were no significant associations between T_{MVC}, RTD_{PEAK}, or $k_{RTD\text{-}SF}$ (EE and VF) and any shooting performance in senior basketball players (r = −0.481–0.481, p = 0.15–0.55) or in both groups combined (r = −0.366–0.271, p = 0.16–0.87).

Significant positive large associations between $k_{RTD\text{-}SF}$ of elbow extensors and volar flexors were calculated for senior group (r = 0.677, p < 0.05) and when both groups were evaluated together (r = 0.615, p < 0.001), while associations between $k_{RTD\text{-}SF}$ of elbow extensors and volar flexors in junior group were not statistically significant (r = 0.514, p = 0.72).

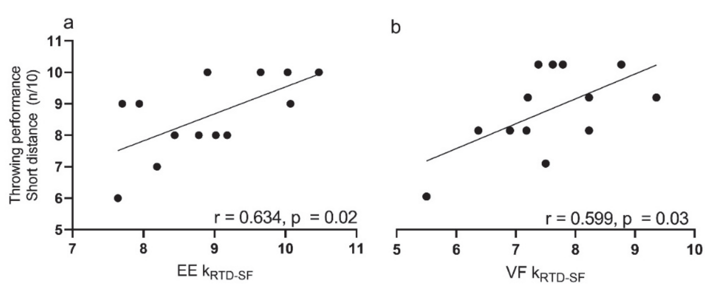

Figure 4. *Cont.*

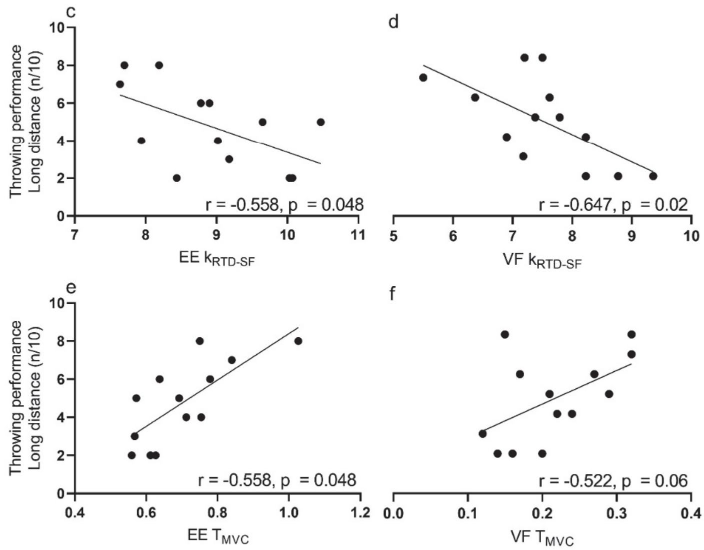

Figure 4. Associations between $k_{RTD\text{-}SF}$ (**a**–**d**), T_{MVC} (**e**,**f**) of elbow extensors (EE) or volar flexors (VF) and shooting performance from short and long distance.

4. Discussion

The first aim of our study was to investigate differences in strength capacities of elbow extensors and volar flexors and shooting performance between junior and senior basketball players. Our results showed similar $k_{RTD\text{-}SF}$ of both muscle groups between juniors and seniors regardless of significant differences between the two groups regarding training history, body mass and BMI. Similar values were also observed for T_{MVC} of both groups, while juniors had significantly greater RTD_{PEAK} (normalized to body weight). Seniors showed better shooting performance only at short distance compared to junior players. The second aim was to investigate associations between strength capacities and shooting performance. Significant associations between $k_{RTD\text{-}SF}$ of both muscle groups and shooting performance were found only in juniors. Our results revealed significant positive association between $k_{RTD\text{-}SF}$ of elbow extensors, volar flexors and shooting performance from short distance. On the contrary, a significant negative large association was found between $k_{RTD\text{-}SF}$ of both muscle groups and shooting performance from long distance. T_{MVC} of elbow extensors was found to have a significant positive large association with shooting performance from long distance. Our third aim was to investigate associations in $k_{RTD\text{-}SF}$ of elbow extensors and volar flexors. Our results showed significant positive large associations between $k_{RTD\text{-}SF}$ of elbow extensors and volar flexors.

In this study, we investigated the $k_{RTD\text{-}SF}$, T_{MVC}, and RTD_{PEAK} of two major groups of arm muscles that generate force that is necessary for the execution of the basketball shot. RTD-SF has already been shown to be sensitive to changes in neuromuscular function associated with age [2] and disease [6]. As it was shown that explosive strength training positively influences shooting accuracy in basketball players [7], and moreover, there are some indices that maximum strength of elbow extensors is positively associated with shooting accuracy in the three-point shot, our goal was to further investigate the relationship between upper limb strength capacity and shooting performance. We hypothesized that a sport-specific movement that is constantly repeated (such as basketball shooting) might have an influence on strength capacities ($k_{RTD\text{-}SF}$, T_{MVC}, and RTD_{PEAK}) of the responsible muscle groups, and in addition, it might be dependent on the training history and physical development. On this basis, we evaluated differences between junior and senior basketball players in terms of $k_{RTD\text{-}SF}$, T_{MVC}, and RTD_{PEAK} of EE and VF. The senior basketball players had significantly longer participation in basketball training and consequently greater experience and completed maturation.

Previous studies have shown that players with more training experience had better free-throw performance compared to less-experienced players [12,14]. Moreover, it was shown that explosive strength training of upper and lower limb improves basketball shooting accuracy [7]. In our study, we investigated shooting performance from shorter and longer, as different shooting distances may require different involvement of muscle strength capacities. Although it is known that muscle growth is occurring in boys until 17.5 years of age [19], our results showed that juniors and seniors had similar strength capacities of elbow extensors and volar flexors, with the exception of RTD_{PEAK}. Significantly larger normalized RTD_{PEAK} in junior players can be explained with their lower body mass index (Table 1), since it is known that lean body mass is associated with greater RFD/RTD [20]. On the other hand, differences in abilities such as $k_{RTD\text{-}SF}$, which is independent of the body mass and muscle size, have not yet been investigated in relation to age. T_{MVC} of elbow extensors, volar flexors as well as $k_{RTD\text{-}SF}$ values of both muscle groups showed similar values in junior and senior basketball players (Table 3). There is a paucity of literature analysing the differences in muscle capacity between junior and senior elite basketball players, especially regarding the upper body. A previous study reported that senior basketball players produce significantly higher absolute power with lower extremities [21]. Our data suggest that there is no difference in neuromuscular quickness (as tested by $k_{RTD\text{-}SF}$), between juniors and seniors. On the other hand, some studies that assessed shooting and passing actions showed that more experienced basketball players exhibit a shorter duration of muscle activation of the arm muscles [15,16]. This could be due to the changes in motor pattern activity associated with increasing skill [22] and not due to the changes in neuromuscular quickness. In accordance with previous studies [12,14], we have also confirmed that the players with more training experience have better shooting performance, but only from short distance. It is known that the shooting movement pattern changes with greater shooting distance, while its accuracy significantly decreases [23]. Overall, our results suggest that senior players do not have higher strength capacities compared to junior players, while they are equalized in shooting performance at long shooting distance. Thus, we can reject our first hypothesis.

Shooting performance was related with $k_{RTD\text{-}SF}$ and T_{MVC} only in junior players. This result suggests that muscle abilities such as neuromuscular quickness and T_{MVC} play an important role in shooting performance only in junior players, whereas in seniors their shooting muscles exceed the level of strength capacities required for successful shooting performance. In more experienced players, the shooting performance is influenced by the pattern of muscle activity (i.e., shorter or longer duration from the beginning of muscle activity, lower average activation time) [15,16] and likely not by the capacity of the shooting muscles. A very strong positive association between elbow extensor T_{MVC} and shooting performance from long distance shows that muscle strength is more important for shooting performance from longer distance in juniors compared to seniors. On the contrary there was no associations between T_{MVC} and shooting performance from short distance. Junior players with higher elbow extensors T_{MVC} were more successful at shooting performance from a long distance (Figure 4e), which highlights the importance of muscle strength in the accuracy task from such distance. We can speculate that junior players with a smaller T_{MVC} were closer to their maximum strength capacity when they performed shots from a greater distance. This can be supported with findings from one study, which showed that the accuracy decreases when the shot is performed closer to the maximal strength capacity [24]. Such associations have been only approaching statistical significance for volar flexors. Likely, it seems that the elbow extensors play a more important role than wrist muscles in providing the force required for the ball to reach the basket at greater distances [11]. On the other hand, RTD_{PEAK} was not associated with shooting performance which could be explained by the fact that basketball shots are not performed under conditions that acquire maximal rate of force development.

Significant large positive associations were calculated between $k_{RTD\text{-}SF}$ of both muscle groups and the shooting performance from short distance in juniors, while $k_{RTD\text{-}SF}$ of both groups was in large negative association with long distance. It seems that the execution of the shot from short distance was better suited to junior players with greater $k_{RTD\text{-}SF}$, while the opposite holds true for the long-distance shots. A negative association between $k_{RTD\text{-}SF}$ and shooting performance from long distance indicates that players with greater $k_{RTD\text{-}SF}$ have worse shooting performance from long distance. It is already known that basketball shots are performed at higher velocities as the distance from the basket is increased [13], while lower velocities are related to greater movement accuracy [25]. It has been shown that weaker players who are unable to generate sufficient force must use a strategy of generating greater segmental velocities in order to execute a shot [26]. Shot execution at higher velocities (due to the greater distance) increases body segments movement variability and decreased movement consistency [27], while shooting performance at lower velocities provides additional time and thus allows players to perform movement corrections with visual and proprioceptive feedback [28]. This could be supported by the results of another study in which novice handball players reduced their shooting accuracy when the shooting speed was increased, while this had no effect on the shooting accuracy of expert players [29]. However, we did not measure the kinematic characteristics of shot execution, which would be valuable information for further explanations of measured associations.

In addition, similar investigation on a larger sample size would be needed for further conclusions together with the kinematic analysis of the shot from few shooting distances, while contribution from lower limb should be also considered. Finally, although the sensors used to acquire force data were high-quality load cell models, the reliability of the exact set-up, as used in this study, has not been checked before. The inter-repetition reliability of the outcome variables was, however, mostly very good. Notably, RFD_{PEAK} had $k_{RTD\text{-}SF}$, which supports that the latter could be an important addition or alternative to commonly performed assessments (T_{MVC} and RTD_{PEAK}).

5. Limitations of the Study

An important limitation of our study is the lack of data about the kinematics of the shot execution (especially movement velocity), which could further explain the relationship between shooting performance and strength capacity. There are potentially other additional variables that influenced the shooting performance and were not controlled (e.g., release angle, release height, physical characteristics of the players, additional basketball skills and movements that occur before shot, the power generated by the leg muscles, etc.). Moreover, only male gender was evaluated so our conclusion refers only to young male basketball players.

6. Conclusions

This was the first study to investigate differences in $k_{RTD\text{-}SF}$ and other strength capacities between juniors and seniors with significantly different training histories. It appears that the specific training history (performing basketball shot) has no influence on neuromuscular quickness of elbow extensors and volar flexors. Our results suggest that strength capacities, specifically T_{MVC} is a limiting factor for successful shooting performance only in juniors, while in seniors there was no associations with strength capacities and shooting accuracy. This should be taken into account in training programmes of young male basketball players. Appropriate strength capacities, specifically maximum strength of elbow extensors should be developed for successful shooting performance for longer distance in young male basketball players. Detailed kinematic assessment of shooting performance should be measured in the future to confirm our assumptions that players with higher $k_{RTD\text{-}SF}$ use higher movement velocities at longer shooting distance, resulting in poorer shooting performance.

Author Contributions: Conceptualization, N.Š.; methodology, D.S., N.Š., and Ž.K.; software, N.Š.; formal analysis, D.S., N.Š., and Ž.K.; investigation, D.S.; resources, N.Š.; data curation, D.S. and Ž.K.; writing—original draft preparation, D.S.; writing—review and editing, N.Š. and Ž.K.; visualization, N.Š.; supervision, N.Š.; project administration, N.Š.; funding acquisition, N.Š. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: Authors thank a student at the University of Primorska, Jure Muršec, for his help at subject's recruitment and data acquisition.

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4

Supramaximal Eccentric Training for Alpine Ski Racing—Strength Training with the Lifter

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Featured Application: The Intelligent Motion Lifter is a new mechatronic strength training device that allows safe and effective strength training with supramaximal loads.

Abstract: Eccentric muscular work plays a large role in alpine ski racing. Training with supramaximal eccentric loads (SME) is highly effective to improve eccentric strength but potentially dangerous. Most SME training devices do not allow the athlete to move a barbell freely as they would when performing conventional barbell training. The Intelligent Motion Lifter (IML) allows for safe SME training with a free barbell and no spotters. The IML can be used for free barbell training: a spotter for normal training, eccentric only, concentric only, and squat jumps. It is also a training and testing device for isokinetic and isometric exercise. This commentary addresses the necessity of eccentric training for elite alpine ski racers, the development of the IML and its use in training.

Keywords: eccentric; alpine ski racing; strength training; supramaximal loads; athlete safety

1. Eccentric Exercise in Alpine Ski Racing

Scientific analysis of world class Swedish alpine ski racers in the 1990s [1,2] showed that eccentric muscular work predominated over concentric work in the disciplines of slalom, giant slalom and super G. More current work with elite Swiss racers corroborated this [3–5], with Vogt and Hoppeler stating that alpine skiing is “the only sport activity dominated by eccentric muscle activity” [5].

The introduction of carving (greater side-cut) skis in World Cup ski racing in 1999 changed ski turns [6]. Ferguson [7] concluded that ski racing is characterized by isometric and eccentric muscular actions. New studies with Austrian [8] and French [9] elite ski racers have indicated that a “quasi-isometric” phase exists in ski racing and that this phase of the ski turn has been overlooked but must be considered.

There is still an incomplete understanding of what is happening during a high-speed ski turn. More research is needed for a full understanding of the metabolic and muscular functional demands of ski racing [10], and there is “a lack of functional and biomechanical understanding of the performance relevant parameters” in ski racing [11].

The dominance of eccentric muscular actions in ski racing can be debated, but eccentric muscular control is important in the sport. Gravity propels the ski racer down the hill [12,13] and the racer must efficiently use potential energy to maintain speed on a racecourse. A kinematic analysis of a World Cup slalom race [13] found that faster racers better controlled the dissipation of potential energy and could more effectively reduce ground reaction forces compared to slower performers. Reid et al. [14] also demonstrated that more energy is dissipated in skidded turns than in carved turns with Norwegian national team ski racers.

We believe that high levels of eccentric strength are necessary to control the dissipation of energy during a skiing turn. Higher strength levels allow the ski racer to work with less relative strength, which may lead to more control in turns (less energy dissipation) and less fatigue during races.

Swiss sport scientists working with the Swiss ski team [3] have built an "Eccentric-Trainer". This special cycle ergometer forces the athlete to eccentrically "brake" the machine to achieve the selected power output and cadence. They found that the ability of the racer to precisely control the eccentric work correlated with International Ski Federation points, which is the system of grading ski racers' racing success. The better control of the eccentric work, the better the ski racer.

The effectiveness of eccentric training in improving maximal strength has been known for some time [15]. The most effective uses of eccentric training seem to be high speed eccentric work and heavy eccentric loading [16]. Many athletes employ supramaximal eccentric training (SME) to improve maximal strength, which may improve performance. World class powerlifters can use 105–110% of their one repetition maximum and lower-level athletes can use 120–130% for SME training [17].

The Norwegian alpine ski team trained with SME squats regularly in the 1990s [17]. A minimum requirement for the squat (hip joint at least same level or lower than knee joint) was 2.5 times bodyweight for the men's Europe and World Cup teams. They also tested for maximal eccentric force with a negative (from top to bottom with control) squat.

Elite sport training centers have developed their own SME squat machines in Austria [18], Norway [17] and Sweden [19], and as mentioned above, the Swiss have designed an eccentric cycle ergometer for ski racers [3]. There are anecdotal references of athletes using supramaximal squats to prepare for ski racing. Bode Miller, a very successful American ski racer, built his own training device in order to perform eccentric squats. We have had personal communications with Canadian and American coaches and know that supramaximal eccentric squats are used in the training of alpine ski racers in other nations. In reviews of the training of alpine ski racers, eccentric training is recommended [20,21].

In a recent review of nine different eccentric training devices [22], the Intelligent Motion Lifter© (IML), from Intelligent Motion GmbH (Wartberg an der Krems, Austria) is the only device which allowed the athlete to move the barbell freely in all planes as they would when performing conventional barbell training.

Free weights, when compared to machines, allow movement in multiple planes, require balance, and mimic natural acceleration and velocity patterns, resulting in a greater transfer of training effect [23]. Electromyographic (EMG) activity is greater when training with free weights, perhaps due to the action of stabilizing muscle groups [24]. A free barbell bench press elicited more muscle activity than a machine bench press [24], and free weight squats showed 43% higher EMG activity than Smith machine squats [25].

Weight releasers are a cost-effective method for barbell SME training, and their use has been documented in scientific studies [26–28]. However, this system is strenuous for coaches or helpers and the athlete must have very good lifting technique to ensure that the two releasers hit the floor simultaneously.

Patterson and Raschner [29] reported a case study with an Austrian world champion ski racer utilizing the Intelligent Motion Lifter© (IML), from Intelligent Motion GmbH (Wartberg an der Krems, Austria) for SME training.

Coaches and athletes must be aware that SME barbell squat training is extremely strenuous and potentially dangerous. Spotters must be properly trained to safely spot the squatter, and SME training requires multiple spotters. The IML makes safe SME barbell training possible without spotters.

2. Development of the IML

The initial goal was to develop a device to allow safe SME training. A high priority was that the barbell would have 100% freedom to move in all three planes during SME loading, so that the normal demands of free weight training would be met (see Figure 1).

Figure 1. The Intelligent Motion Lifter© (IML) prototype in 2010. From left to right: bench press, bench pull and squat.

A needs analysis concluded that the following conditions must be met:

- The device will safely and quickly stop the bar if the athlete "fails" during a lift.
- The barbell will move freely (in all planes) during the eccentric portion of lift.
- There will be no external adjustments to the barbell load during a multiple repetition set.
- Automated assistance will be provided to safely return the barbell to the starting position of the eccentric phase (no concentric phase for the athlete).
- The range of motion (top and bottom of lift) can be adjusted for each athlete.
- The range of motion for all lifts performed by an athlete will be saved by the device.
- The device will provide training data which can be exported for training documentation.
- The machine can be used as a spotting device during normal lifts.
- The machine will have dimensions similar to a normal power rack.
- The machine cannot be used without a coach or training partner to operate the device.

The Lifter was originally conceived for SME training, but further developments allow the device to be used for concentric-only training, isometric training, and testing, and as a spotter for normal barbell lifts and jumping. The additional functions that were added to later versions of the Lifter included:

- Automated assistance will be provided to safely return the barbell to the starting position of the concentric phase (no eccentric phase for the athlete).
- The arms will move fast enough that an athlete can perform a loaded squat jump or countermovement jump and the arms will catch the barbell at the top of the jump.
- Isokinetic movements can be performed with a bar attached to the arms in both concentric and eccentric movements. The force applied by the athlete on the arms will be measured and recorded.
- Isometric testing and training can be performed with a bar coupled to the arms. The force applied to the bar by the athlete will be measured and recorded.
- The velocities of the concentric and eccentric phases of the isokinetic movements can be independent of each other; one phase can be faster than the other.

These conditions were taken into consideration when developing and constructing the IML. The IML is a safe automated mechatronic SME device which requires one operator and no external load adjustments during training. A prototype of this training device was introduced at the International Conference on Strength Training 2010 [30].

3. Description of the IML

The IML is essentially two lifting systems utilizing mechatronic technology. Each system has a lifting arm and consists of a column with a drive spindle, guide rails and a synchronized servomotor. The two drives can be virtually coupled via the software and the arms can operate independently of each other. The system is controlled by a real-time capable central processing unit (CPU).

The arms move with the barbell as it is lowered or raised without contacting the barbell. The displacement and speed of the barbell is tracked by two draw-wire encoders attached to the barbell with lightweight plastic plates, which slide onto the barbell similar to weight plates (see Figure 2).

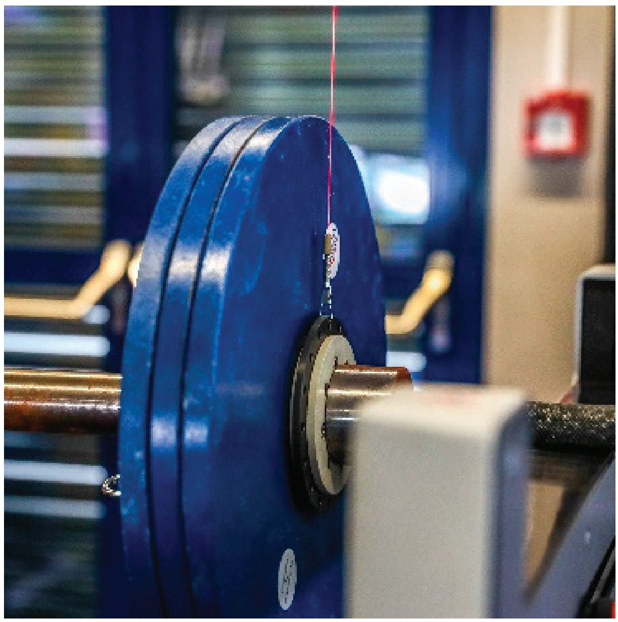

Figure 2. The draw-wire and plate of the draw-wire encoder.

The height difference between the two arms is automatically limited to 100 mm. If the difference exceeds 100 mm, the machine will automatically move one of the arms to stay within 100 mm. The arms can work independently so that the athlete must balance the bar as in a normal free barbell squat. The arms can also be programmed to work together, so that the barbell still moves freely, but the athlete does not have to concentrate on keeping the barbell level. The arms can be programmed to follow the barbell at a distance of 12.5 to 100 mm, allowing a tolerance limit for keeping the barbell level.

A free barbell can be raised and lowered to heights of 1850 mm and 550 mm, respectively, and the simulation bar can be raised and lowered to heights of 1750 mm and 450 mm, respectively. The maximum barbell load is 400 kg and the maximum simulated load is 250 kg.

The maximum velocity of the arms is 2000 mm/s and the minimum velocity is 10 mm/s. The maximum acceleration of the arms (full load or empty) is 4000 mm/s^2.

The entire machine is controlled by a mobile handheld control unit, which has a touchscreen display, an emergency stop switch, and an override switch. This unit is attached by cable to the IML. There is also a screen on the IML for athlete instructions.

4. Safety Standards of the IML

Various safety functions ensure maximum safety during training with the IML. The IML has two CPUs which monitor the programed safety elements. These are:

- All emergency stop switches,
- The speed of the barbell,
- The displacement of the barbell, and
- The bottom movement limits of the exercise.

There are four emergency switches. Two are on the sides of the IML, one is on the handheld control unit and one is mounted on the front wall facing the athlete at foot height (see Figure 3). If an emergency switch is activated, the arms will stop. The programmed movement range and speed of the barbell is monitored by the safety CPUs. In order to actively move to the lowest positions in training, the override switch on the handheld unit must be pressed during the entire exercise. If the override switched is not pressed, the arms will automatically stop.

Figure 3. The present IML model: squat top position and squat bottom position.

All safety elements, including the safety CPUs, have the highest safety level in control technology and automation available at the time of manufacture: safety integrity level (SIL) 3. A discussion of how safety standards and risk assessment systems for manufacturers and approval agencies are developed has been presented by Stavrianidis and Bhimavarapu [31].

An additional safety feature has been developed. In the bench press, the barbell or the coupled bar is lowered to the chest and the athlete may fear that the bar will crush them. A mechanical safety pin system can be placed onto the floor supports and this will brake the arms so that the coupled bar or barbell will not crush the athlete. The safety CPUs prevent this, but the safety pin system assures the athlete that he or she is safe (see Figure 4).

Figure 4. The mechanical safety pin system.

5. Training and Testing with the IML

5.1. Training Mode

5.1.1. Training with a Free Barbell

First, the upper and lower limits and lift off position of the lift are set for the athlete. The number of sets and repetitions can be prescribed. The coach can operate the machine manually, or program the number of sets, repetitions, and rest periods between repetitions and sets. The velocity and the acceleration of the arms can be programmed, dictating the speed of movement and the "hardness" or "softness" of the change of direction between the raising and lowering of the arms. There is also an "aggressiveness" setting, which controls how quickly the arms follow the movement of the barbell.

5.1.2. Spotter Mode

The arms are positioned under the barbell (but without contact) and follow the path of the bar at a predetermined distance (12.5–100 mm). The athlete is able to train normally with no help from the machine. When the set is done, the athlete can rack the bar onto the arms (see Figure 3).

5.1.3. Eccentric Only Mode

The athlete loads the barbell onto the back from the lift off position and lowers the barbell under control to the lower limit. The arms lift the barbell back to the lift-off or upper limit. The rest at the top can be programmed or determined manually by the coach.

5.1.4. Concentric Only Mode

The athlete starts with the barbell at the lower limit and lifts the barbell to the upper limit. The arms lower the barbell back to the lower limit. The rest at the bottom can be programmed or determined manually by the coach.

5.1.5. Throw or Jump Mode

The barbell is caught by the device in loaded jumps or bench press throws (or other dynamic exercises). For a jump, after lift-off, the athlete lowers into a controlled countermovement and when the lower limit is reached, a beep signals the athletes that he/she can jump. The arms are then "triggered" and once the barbell starts to move upwards the arms will follow the barbell up (velocity of arms is 2000 m/s) and catch the bar at a height of 1850 mm.

5.2. Training with the Simulation Bar

As in the free barbell modes, the upper and lower limits of the lift are set with the athlete. The number of sets and repetitions can be set. The coach can operate the machine manually, or program the number of sets, repetitions, and rest periods between repetitions and sets. The arms can be locked in place or allowed to move in the horizontal plane up to 450 mm (see Figure 5). Force sensors in the arms allow the force on the simulation bar applied by the athlete to be precisely recorded during training. The force measurements evaluate the exercise and can regulate simulated loads.

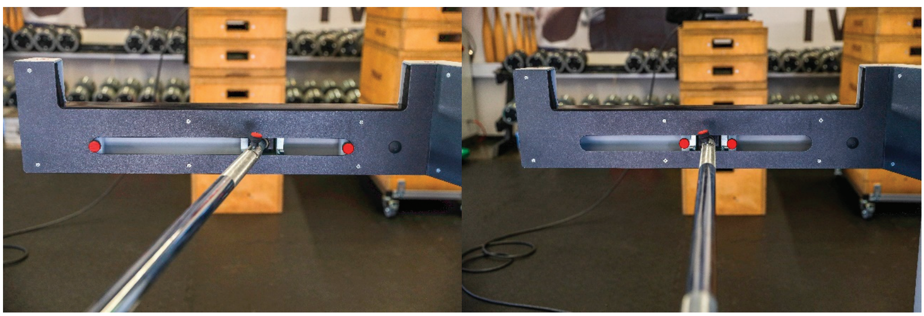

Figure 5. The simulation bar free (**left**) and locked (**right**).

5.2.1. Isokinetic Mode

The arms move the simulation bar at a pre-selected constant velocity (50–400 mm per second) between the set upper and lower limits. The eccentric and concentric phases can be run at different velocities. This is isokinetic training. This can also be used as a roller simulator for skiers and snowboarders. A board is attached to the device and that athlete absorbs the rolls as the arms move up and down.

5.2.2. Simulated Load Mode

The simulated load is set in kilograms and can be configured for both the concentric and the eccentric movement direction and can be constant, increasing or decreasing. For example: Training exercise: squat, eccentric: 220 → 180 kg; concentric: 150 → 180 kg. At the start of the motion (upper motion limit), 220 kg is simulated. As the barbell continues downwards, the weight is reduced to a training load of 180 kg at the lower motion limit. Once the lower limit is reached, the controls switch to a training load of 150 kg. As the barbell moves upward, the load is linearly increased until 180 kg is reached at the upper limit. When the upper limit is reached, the controls again switch to the setting for the eccentric movement.

5.3. Measuring Strength with the Simulation Bar

5.3.1. Isokinetic Measurement

The simulation bar is attached to the arms. The arms move up and down between the defined upper and lower limits at a constant speed. The velocity and the acceleration set by the coach define the speed of the bar and the hardness of the change of direction. The force applied to the bar is measured.

5.3.2. Isometric Measurement

For isometric measurement, the position of the simulation bar is set manually, and the arms hold the configured position. The force applied to the bar is measured statically.

6. A Case Study—Training with the IML

6.1. Methods

A 30-year-old Austrian female ski racer (winner of multiple Olympic and world championship medals) trained with the IML. The general physical preparation (GPP) of this athlete was from May to October 2011 (see Table 1). Height and weight during the GPP were 166 cm and 65.0 kg, respectively. As an athlete training at the Olympic Training Center, Department of Sport Science, University of Innsbruck, she was given verbal and written descriptions of training and informed of the risks of associated with participation in elite sport and training. She signed an athlete agreement, which included an informed consent for training. She also underwent a medical check up to ensure that there are no contraindications to participating in her sport or training at the center. The athlete agreement (#01/2011) was approved in 2011 by the institutional review committee of the Department of Sport Science of the University of Innsbruck and the board for ethical questions of the University of Innsbruck.

The SME training phase was performed with squats, over a four-week period, with two SME sessions per week. At the start of this phase, a one-repetition maximum (1RM) test was performed. The depth of the squat was similar to that of a powerlifting squat. At the bottom of the squat, the top surface of the legs at the hip joint was lower than the top of the knees.

Most squat sessions had at least five eccentric only loading (EOL) sets with 2–4 repetitions, and 4–6 heavy sets (1–3 repetitions) of normal squats (see Table 2). The athlete would lower the bar to a 5 s count, and the IML would return the bar to the starting position. EOL sets were alternated with normal squat sets, with a rest between 3–6 min. A maximum total of 12 heavy sets of squats were performed. Training loads were progressively increased. Training volume was calculated, but only for loads of 100 kg (89% of original 1RM) or more. Leg training sessions also included lunges, Romanian deadlifts, and hamstring curls (2–3 sets and 6–8 repetitions). The last SME workout was 15 July 2011. During a five-week block in July and August, the focus was on ski training in Switzerland and New Zealand. Leg strength maintenance in this block included five leg training sessions, with three sessions utilizing one-legged squats (three sets of eight repetitions) and two sessions of normal squats (4–5 sets, up to 110 kg, 3–4 repetitions). The last week of August was a regeneration week. Strength training resumed on 6 September 2011 and a 1RM test was performed.

Table 1. Periodization of strength training in the general physical preparation (GPP). CON: conditioning camp, SKI: ski racing camp, RG: regeneration week.

MONTH	MAY	JUNE	JULY	AUGUST		SEPTEMBER		OCTOBER
PHASE	GENERAL PREPARATION PERIOD			SPECIAL 1		REGENERATION – 1 WEEK	SPECIAL 2	SPECIAL 3
CAMPS		CON		SKI	OVERSEAS		SKI CAMPS EVERY WEEK, VARIED LENGTHS	
WEEKS IN CYCLE	2	5	4	2	3		4	3
STRENGTH	STABILITY	MAXIMAL	SME	MAINTAIN			POWER, MAINTAIN STRENGTH	
WORKOUTS (WO) SETS (S) REPS (R)	6 WO	10 WO 3–4 S, 3–5 R	7 WO 6–10 S, 2–4 R	2 WO 3–5 S, 3–8 R	2 WO 3–5 S, 3–8 R		HEAVY SQUAT: 2–5 S, 1–5 R; SPEEDSQUAT: 3–5 S, 5–8 R; JUMP: 2–5 S, 5–8 R	

Table 2. Squat training sessions in the supramaximal eccentric training (SME) phase. Dates are day and month. L = load in kilograms, R = repetitions, N = normal squats, EOL = eccentric only loading, 1L = one-legged squats. Training volume was calculated as training load × repetitions.

21.06	L	R	27.06	L	R	01.07	L	R	04.07	L	R	08.07	L	R	11.07	L	R	15.07		
N	40	15	N	40	15	N	40	15	N	40	6	N	60	6	N	40	10	N	40	6
N	60	8	N	60	8	N	60	8	N	60	8	N	80	5	N	60	6	N	60	6
EOL	60	3	EOL	80	3	N	80	5	N	80	5	EOL	110	4	N	80	5	N	80	5
N	80	4	N	80	5	N	90	3	EOL	100	2	N	100	3	N	90	4	N	100	3
EOL	80	3	EOL	90	3	EOL	100	2	N	100	3	EOL	110	4	N	100	3	EOL	110	3
N	90	3	N	90	3	N	100	3	EOL	110	3	N	110	3	EOL	110	3	N	115	1
EOL	100	3	EOL	100	3	EOL	110	2	N	100	3	EOL	120	33	N	110	3	EOL	120	3
N	100	3	N	100	3	EOL	120	2	N 1 L	60	3	N	115	1	EOL	110	3	N	120	3
N	105	3	EOL	110	3		115	1	EOL 1L	60	3	EOL	120	3	N	115	3	EOL	125	2
N	110	3	EOL	120	4	EOL	125	2	N 1 L	60	3	N	117.5	1	EOL	120	3	N	120	3
EOL	110	3	EOL	120	4		117.5	1	EOL 1L	75	3	EOL	122.5	3	N	115	3			
EOL	110	3				EOL	130	2	N 1 L	60	3	N	117.5	1	EOL	120	3			
N	115	1				N	120	1	EOL 1L	90	3	EOL	122.5	3	N	117.5	3			
						N	100	6	N 1 L	60	8	N	117.5	3	EOL	122.5	3			
									EOL 1L	90	3				N	120	3			
Workout Volume			Workout Volume			Workout Volume			Workout Volume			Workout Volume			Workout Volume			Workout Volume		
N	1060		N	300		N	1252.5		N	2640		N	1450		N	2385		N	1135	
EOL	960		EOL	1590		EOL	1170		EOL	2420		EOL	2335		EOL	1747.5		EOL	1060	
Total	1720		Total	1890		Total	2422.5		Total	5060		Total	3785		Total	4132.5		Total	2195	

6.2. Results

The subject's 115 kg 1RM squat increased to 127.5 kg (11%) from 21 June to 6 September.

7. Discussion

The athlete and coach considered the 1RM increase of 11% after a four-week block of EOL training followed by six weeks of maintenance training (five weeks skiing with strength maintenance and a regeneration week) a good training result. This increase may have been greater if she had performed a 1RM test one or two weeks after the four-week SME phase. This particular athlete had performed squats for over 15 years, but through most of her career had not trained "heavy" (1–3 maximal repetitions). Coaches and sport scientists concur that maximal absolute strength is best trained with heavy weights and low repetitions [32–34], and her strength gains were largely due to the increased intensity.

The increase in intensity and volume was gradual; this athlete was not familiar with heavy squats. The training volume on 4 July was so high because one-legged squats were performed. The athlete felt tired physically and psychologically and did not want to perform heavy squats, so single leg squats were used. However, as she progressed in the workout, she managed to do two sets of EOL single leg squats with 90 kg. The coach must understand the psychology of an athlete lifting heavy weights. The intensity is always relative to the athlete and their personal 1RM. The last SME session had the highest intensity with relatively low volume. The athlete squatted 5 kg more than her original 1RM for three repetitions. In subsequent seasons, this athlete was using as much as 165 kg for EOL squats.

The athlete felt that the increase in leg strength with SME training had a positive influence on her skiing. She also believed that the heavier loads used for squats improved her core stability. Some coaches maintain that heavy squats are one of the best core exercises.

One problem with comparing leg strength with ski racers is that there is no benchmark test. Austrian ski racers are tested with a multi-joint isokinetic leg press, and some nations use a single joint isokinetic leg extension machine; others test with squats. The problem with squats is that technique and squat depth varies from athlete to athlete, and nation to nation. One conditioning coach working with world class female racers insists that his athletes use deep squats similar to weightlifters, in which the hip joint is much deeper than the knee, often with the thighs on the calves. This is often referred to as a full depth squat. Others use a 90° knee angle as the bottom position, but many refer to this as a half squat, because of the minimal depth. In the present case study, the athlete used a depth similar to power lifters, with the top of the thigh below the top of the knee.

The following is mainly anecdotal evidence, but there is very little published work on squats with alpine ski racers. Beate Amdahl (now Amdahl Skorpen) was a Norwegian female powerlifter. At a body weight of 60 kg, she increased her 1RM from 180 kg to 210 kg during two years of eccentric training [17]. It should be clear that as a powerlifter, her competitive goal is to lift as much weight as possible for one repetition in competition. Pernilla Wiberg, a very successful Swedish female ski racer, had a best squat of 170 kg at a bodyweight of 67 kg. The depth of this squat was slightly above the depth of a powerlifting squat. Norwegian scientists have stated that all female Norwegian World Cup ski racers during the 1990s could squat 2.2 times their body weight once (powerlifting squat) [17]. The conditioning coach of one of the most successful male ski racers ever, Andre Kjetil Ammodt, maintained that Aamodt could squat 220 kg at 85 kg bodyweight, or 2.6 times his bodyweight.

Ski racers are using eccentric training to get stronger. A meta-analysis [35] determined that eccentric training is superior for strength and mass gains compared to concentric training, possibly due to the higher loading in eccentric work.

Enhanced strength gains from eccentric training are related to the neural demands of eccentric work. Eccentric movements require less motor unit recruitment than concentric [36], so the recruited motor units receive much more stimulation [37,38]. Nervous system control of eccentric actions is more complex than that of concentric work [36]; thus, neural adaptations to eccentric training are greater than those to concentric training [39].

The increased central nervous system load during SME leads to greater strength gains, but coaches and athletes must be wary of overtraining. In the present case study, SME twice a week elicited satisfactory strength gains without adverse effects. Norwegian sport scientists have recommended that athletes train with SME only once per week [17].

The 1080 Quantum Synchro by 1080 Motion is a new device that also allows SME with a barbell, but in a Smith machine, so the athlete does not have to control the path of the barbell. This is an unnatural way to perform barbell exercises and the athlete does not have to balance the barbell. The 1080 Quantum Synchro can be used with the following forms of resistance: isokinetic, normal mass, isotonic and ballistic. It appears that the eccentric barbell movements are isokinetic, but isokinetic movements do not exist in sport. It has a maximum eccentric resistance load of 325 kg; the IML can be loaded up to 400 kg. The 1080 Quantum Synchro can also be used with a cable system to allow sport-specific movements. This device looks very promising, and has been used in research [40].

The IML allows an athlete to train heavy with EOL squats with just one coach or partner to control the IML. Eccentric training is becoming more popular in GPP strength programs for alpine ski racers, and the authors believe that this trend will continue.

8. Conclusions

Properly planned strength training programs incorporating SME, which the IML supports, can improve maximal strength. The use of the IML as a SME training device for athletes who do not have an advanced level of strength is not advised. Athletes need to have the technical abilities and adequate strength to manage supramaximal loading. Athletes without high strength levels can utilize the device for other methods of training.

Author Contributions: Conceptualization, C.P. and C.R.; Methodology, C.P.; Investigation, C.P.; Data collection and curation, C.P.; Writing—original draft preparation, C.P.; Writing—review and editing, C.P. and C.R.; Supervision, C.R.; Photography, C.P. and C.R. All authors have read and agreed to the published version of the manuscript.

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5

Effectiveness of Positive and Negative Ions for Elite Japanese Swimmers' Physical Training: Subjective and Biological Emotional Evaluations

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Abstract: The purpose of this study is to examine the subjective and objective arousal of elite swimmers during physical training under a positive and negative ion environment. The participants were 10 elite Japanese collegiate swimmers participating in the Fédération Internationale de Natation (FINA) Swimming World Cup (age: 20.80 ± 1.39, five males and five females). Each participant went through two experiments (they were subjected to both the positive and negative ion environment and the control environment) within a four-week interval. The training task was a High-Intensity Interval Training (HIIT) routine for the swimmers. The subjective arousal state was measured using a Two-Dimensional Mood Scale (TDMS). In addition, biological emotional evaluations in the form of an electroencephalogram (EEG) were conducted to assess the arousal state of the elite swimmers. The examination of the change in the arousal level at rest and during training demonstrated that both subjective and objective arousal levels were significantly higher in the positive and negative ion environment than in the control environment. In addition, the average training performance scores were also significantly higher in the positive and negative ion environment than in the control environment. This study posits that the positive and negative ion environment has a positive effect on sports training.

Keywords: training environment; sports; athletes; interval training; biological emotional evaluation; sports sciences

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1. Introduction

Arousal is a human psychological state and is defined as being "worked up" or energized [1]. In addition, Oxendine [2] proposed that high levels of arousal would benefit, or be essential for, maximal performance; thus, several studies investigated the relationships between arousal and sports performance [1,3,4]. Yamazaki and Sugiyama [4] examined the relationships between subjective arousal level and sports performance and the results indicated that, among Japanese collegiate badminton players, athletes with higher arousal levels had significantly higher shot success rates. In addition, Fronso et al. [5] used an electroencephalogram (EEG) to assess the biological arousal level in Olympic athletes participating in air-pistol shooting, and investigated the relationships between arousal level and sports performance. The results demonstrated that higher levels of arousal were associated with controlled shooting performance. Although subjective evaluations about arousal level have been conducted using questionnaires [1,4,6], few studies about the biological evaluations of psychological arousal level have been attempted.

Air ions are small particles that exist in nature and are positively or negatively charged molecules or atoms in the air [7]; positively charged ions are positive ions and those negatively charged are negative ions [8]. In addition, air ions containing positive and negative ions have certain abilities such as purification of the atmosphere and deodorization [9]. Thus, several studies have been conducted on the relationship between air ions and human emotions.

Previous studies on the relationship between air ions and emotion in humans have been conducted [10]. Flory et al. [11] conducted an experiment where 18 women stayed in a high-density ion environment for over 12 consecutive days and the results indicated that the high-density negative ion environment reduced depression. In addition, other studies that examined the relationship between negative ions and depression [12–15], lower stress [16], and increased well-being [17] have been conducted. Several studies also suggest that relationships exist between positive ion environments and human emotion [10]. For instance, Gianinni et al. [18] examined the correlation between positive air ions and emotion and found that anxiety and excitement significantly increased under this condition. In addition, the relationship between positive ions and feelings of unpleasantness, irritation and anxiety has been verified [18,19].

Although there is some skepticism in the study of ions, the results of the above-mentioned studies confirm that they are connected to emotional changes. In addition, little research has been done on the relationship between positive and negative ions and the emotion and performance of athletes in the field of sports science, and no such research is found in Japan. Thus, the purpose of this study was to examine the subjective and objective arousal of elite Japanese swimmers during physical training in a positive and negative ion environment.

2. Materials and Methods

2.1. Participants and Study Design

Institutional review board approval was obtained from the corresponding author's research institute (National Institute of Fitness and Sports in Kanoya, Institutional Review Board, No.11-6). The participants were informed of the instructions and purpose of this study before the experiment.

The participants were 10 elite Japanese collegiate swimmers participating in the Fédération Internationale de Natation (FINA) Swimming World Cup (age: 20.80 ± 1.39, 5 males and 5 females). Each participant underwent two experiments within a four-week interval. Two types of experimental environment were prepared: a condition in which positive and negative ions were filled up the atmosphere in the experimental room (PNI condition), and a condition in which ions were not generated (control condition). The conditions were blinded by randomly changing the experimental environment to prevent the participants from knowing to which condition they were subjected. The details of randomization are described as follows.

The first experiment was conducted within two days. On the first day, we created a PNI condition and conducted experiments while filling the atmosphere with air ions. The participants were randomly assigned and trained in one of the two environments (in the first experiment, three female and two male athletes performed in the PNI condition). After the experiment in the PNI condition was completed, the experimental laboratory was opened for one day to stop the ionizers and release the PNI from the room. Thereafter, it was confirmed that there were no PNI and the remaining five people (three women, two men) conducted experiments in a control condition. Four weeks after the first experiment, the participants underwent the same procedure and the second experiment was conducted.

The PNI condition was delivered by six Plasmacluster^{TM} ionizers (Sharp Corporation, Sakai-shi, Osaka, Japan) and exposed the participants to positive and negative ions (147,000–164,000 PNI/cm^3). The details of the process for generating positive and negative ions were based on previous research [8]. First, molecules in the air are decomposed by applying positive and negative high voltages to each discharge brush electrode of the ion generation devices, and the devices generate positive ions and negative ions [20].

The ion concentrations were determined by an ion counter (MY1210S, Asahi System Inc., Osaka-shi, Osaka, Japan) by means of the double concentric circle tube method [20]. The room condition was a temperature of 24.0 °C ± 0.5 and humidity was 60% ± 2.0.

The experimental procedure is as follows (Figure 1). First, participants were asked to put on an EEG device for two minutes to investigate their baseline degree of arousal before training. An EEG is an electrical signal generated by the brain and can be used to measure the psychological state of humans in real time. The participants then answered a questionnaire which evaluated their subjective emotional state before the training. A training task was then assigned. The training task was a High-Intensity Interval Training (HIIT) routine for swimmers. Participants conducted eight sets of 20 s of hard exercise and 10 s of rest using a swimming ergometer (Concept2 Inc., Morrisville, VT, USA) (Figure 2). After 8 sets, participants rested for 10 min and then again performed HIIT for 20 s, with one set at maximum power. After the training task, the average load (W) for 8 sets of intervals and the maximum power set of training load (W) after a 10-min rest were evaluated. The training load was set to the load used by the participants in their daily practice. Thus, the training load was set to eight for males and six for females. Thereafter, the EEG of the participants was measured for two minutes to investigate their degree of arousal after training, after which they were required to answer a questionnaire again.

In this study, EEG was also measured during interval training but, since it was accompanied by large movements during training, accurate data could not be acquired due to noise. Therefore, the measurement values were compared for two minutes before and after training. In addition, this study used the same method as a previous study [21] that adopted two minutes to investigate the baseline degree of human emotion.

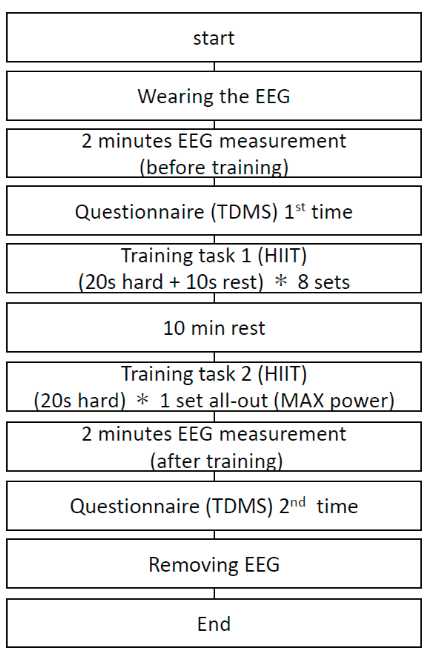

Figure 1. Experimental procedure.

Figure 2. High Intensity Interval Training (HIIT) Training.

2.2. Emotional Evaluation

Subjective emotional evaluation was measured using a Two-Dimensional Mood Scale (TDMS) [22]. The TDMS is composed of eight items and four factors: activity, stability, comfort, and arousal. This study used the arousal score to evaluate the elite swimmers' emotional state.

A biological emotional evaluation in the form of an EEG was also conducted to assess the arousal state of the elite swimmers. In addition, the EEG measurement was used in this study because it is more easily measured in a daily living environment compared to other brain activity measurements. We adopted a simple band-type EEG device (NeuroSky Co., Ltd., Tokyo, Japan) that only measures the front polar area 1 (Fp1) lobe as defined by the international 10–20 system (Figure 3). Since Fp1 is located on the left frontal lobe, there is no need to worry about the possible noise interference caused by hair. The EEG obtained from Fp1 has been found to be suitable for obtaining data on people's psychological condition [23,24]. Thus, this study also assessed the Fp1 to estimate arousal level.

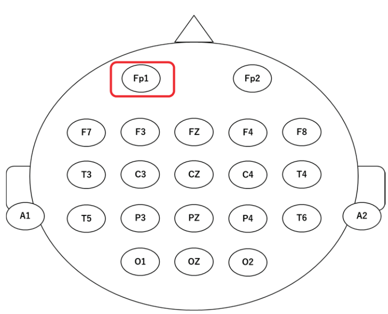

Figure 3. Measurement points of the international 10–20 system.

The electrical activity in the brain is often used as an objective evaluation index that employs biological data. Brainwaves are generally classified into four types according to their frequency range:

0.5–4 Hz: delta waves, 4–8 Hz: theta waves, 8–13 Hz: alpha waves, and 13–40 Hz: beta waves. Emotions are associated with each type [25] (Table 1).

Table 1. Type of brain wave and psychological state.

Type of Brain Wave	Frequency (Hz)	Psychological State
Delta wave	0.5–4 Hz	Non-REM sleep, unconscious
Theta wave	4–8 Hz	Sleep onset, illusion
Alpha wave	8–13 Hz	Relaxed mental state
Beta wave	13–40 Hz	Arousal

This study focused on the beta wave band. The EEG data obtained were recorded in a smartphone and the Kansei Module Logger [26]. This method produced the data output as sensitivity values were used. In addition, the Kansei Module Logger was set so that the occurrence ration of the beta wave band was defined as the arousal level, and the value was easily displayed as a value from 0 to 100. Hagiwara et al. [27] posited that the arousal level output by the Kansei Module Logger correlates with the subjective arousal level. The basic concept of Kansei Module Logger is that it calculates the power ratio between the beta wave bands. The potential difference obtained from the electrodes on the forehead and earlobe of the left Fp1 is amplified by the circuit inside the measuring instrument, digitized at 512 samples/sec, and subjected to the Hanning window processing. The power spectral analysis was then conducted using the fast Fourier transform. EEG data are analyzed every second by the fast Fourier transform, and the amplitude spectra can be obtained in the frequency range of 1–64 Hz. Thus, this study obtained delta, theta, alpha and beta waves. From the obtained power spectrum, the sum of each power in each frequency band was then calculated, and the ratio included in the total of the total power is shown as a relative numerical value. However, the sum of the power of each frequency cannot be used because the amplitude of each frequency band is different. Therefore, we took the average value of the power of each frequency band and obtained the representative value of that frequency band. The calculation method used the following Formula as a standard for analysis.

The average P_x of the x-wave power was calculated by Formula (1), where V_f is the power of the EEG at the frequency f [Hz]. Since this study concerns the beta wave band (13 Hz to 40 Hz), when $x = \beta$, it becomes (13, 40) [Hz], and the numerical value is applied to $(F^x{}_{max} - F^x{}_{min})$ in Formula (1). Next, the sum of the power averages (P_{sum}) in each frequency band is calculated by Formula (2). The ratio (R_x) included in the total power of the beta wave band was calculated in Formula (3).

$$P_x = \sum_{f=F^x_{\min}}^{F^x_{\max}} V_f / (F^x_{\max} - F^x_{\min} + 1) \tag{1}$$

$$P_{sum} = P_\delta + P_\theta + P_\alpha + P_\beta \tag{2}$$

$$R_x = P_x / P_{sum} \tag{3}$$

Based on the above calculation method, the Kansei Module Logger normalized the power ratio that can be taken in the beta band to the value of 0–100.

2.3. Analysis

For subjective data, the difference between the average value of arousal level by TDMS before and after training was used as the change value, and t-test was used to compare the PNI condition and control condition. For biological data, the difference between the average value of arousal measured before training and the average value of arousal measured after training was used as the amount of change. The paired t-test was then used to compare the difference between the PNI condition and the control condition. In the training data, the average load (W) for 8 sets of intervals and maximum power set of training load (W) after a 10-min rest were compared between the PNI condition and the control condition.

3. Results

3.1. Comparison of Changes in Arousal by TDMS before and after Training in PNI and Control Conditions

As a result of comparing the amount of change in arousal by TDMS before and after training in the PNI and the control conditions, the amount of change in the arousal level under PNI condition (M = +7.30, SD = 1.90) was found to be significantly higher than that in the control condition (M = +3.3, SD = 1.24) ($t = 3.52$, $p < 0.01$) (Figure 4).

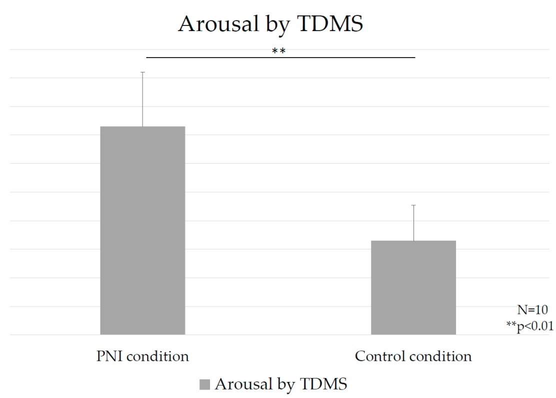

Figure 4. Comparing the amount of change in arousal by a Two-Dimensional Mood Scale (TDMS) in Positive-Negative Ions (PNI) and control conditions.

3.2. Comparison of Changes in Arousal by EEG before and after Training in the PNI and the Control Conditions

As a result of comparing the amount of change in arousal by EEG before and after training in the PNI and the control conditions, the amount of change in the arousal level under PNI condition (M = +8.16, SD = 2.14) was also found to be significantly higher than that in the control condition (M = +2.75, SD = 2.24) ($t = 2.84$, $p < 0.05$) (Figure 5).

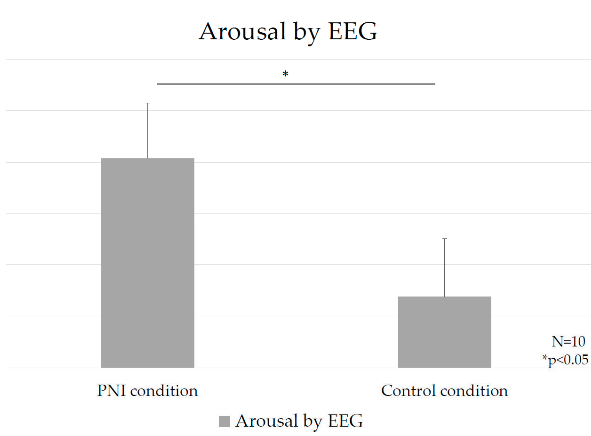

Figure 5. Comparing the amount of change in arousal by electroencephalogram (EEG) in PNI and control conditions.

3.3. Comparison of the Average Load (W) for Eight Sets of Interval Training in PNI and Control Conditions

As a result of comparing the average load (W) of interval training in the PNI and the control conditions, the average load (W) under PNI condition (M = 146.22, SD = 13.54) was shown to be significantly higher than that recorded in the control condition (M = 141.14, SD = 12.32) ($t = 1.46$, $p < 0.10$) (Figure 6).

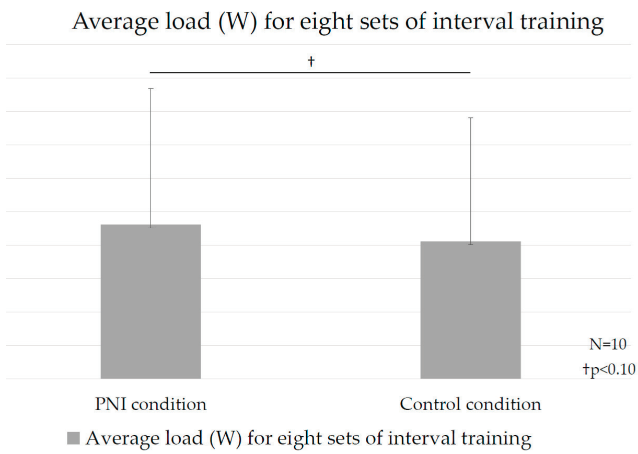

Figure 6. Comparing the average load (W) for 8 sets of interval training in PNI and control conditions.

3.4. Comparison of the Average of Training Load (W) during the Maximum Power Set in PNI and Control Conditions

As a result of comparing the average of training load (W) during the maximum power set in the PNI the and control conditions, the average load (W) under PNI condition (M = 192.78, SD = 19.36) was also found to be significantly higher than that in the control condition (M = 181.67, SD = 16.03) ($t = 1.99$, $p < 0.05$) (Figure 7).

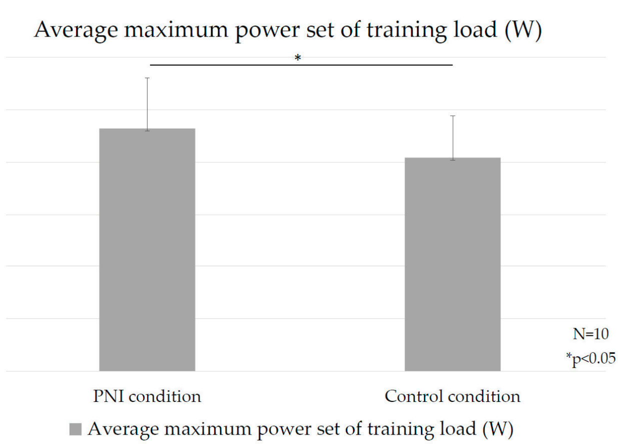

Figure 7. Comparing the average of training load (W) during the maximum power set in PNI and control conditions.

4. Discussion

This study aimed to investigate the psychological effects of both the subjective and objective arousal levels of elite Japanese swimmers during physical training under a positive and negative ion environment.

First, the results of the comparison of the subjective arousal level indicated that the PNI condition significantly improved the arousal level compared to the control condition. Previous studies [12–15] have clarified the relationship between negative ions and positive emotions by using subjective evaluation. In addition, subjective research has also shown the relationship between positive ions and emotions in previous studies [18,19]. In this study, as a result of verifying the subjective arousal level in an environment in which PNI are simultaneously generated, it is suggested that athletes may have a higher arousal level under the PNI condition. These results are considered to be new findings in the literature on PNI and emotions.

Second, the results of the comparison of the objective arousal levels obtained from EEG indicated that the PNI condition significantly improved the arousal level compared to the control condition. A few studies in the past [28,29] tried to clarify the relationship between negative ions and emotions using brain waves. Watanabe et al. [29] examined the effect of negative air ions on EEG, and the results indicated that the alpha wave tended to be higher in the negative ion condition than in the control condition. On the other hand, the results of this study indicated that the PNI condition demonstrated a significantly higher arousal level (beta band power level) than the control condition. Therefore, the results of this study differ from the previous studies that were mentioned earlier. A subjective evaluation study by Charry and Hawkinshire [19] showed that positive ions contribute to the improvement of tension. In this study, since the experiments were conducted in the environment in which positive ions were also generated, it is speculated that positive ions may affect the arousal level extracted from the EEG. As mentioned, it might demonstrate the existence of relationships between PNI conditions, and states of subjective and objective arousal. However, as mentioned previously, there is some skepticism in the study of ions; thus, it would be necessary to further study the relationships between air ions and athletes' emotions in the field of sports science.

Finally, the results of comparing the average load (W) of interval training under the PNI and the control conditions show the average load (W) under the PNI condition tended to be significantly higher than that recorded in the control condition. Moreover, the result of comparing the average of training load (W) during the maximum power set under the PNI condition was that it was recorded as significantly higher than under the control condition.

Several researches have examined the association between physical exercise and negative ions [30,31]. Ryushi et al. [30] demonstrated that, under the negative ion condition, the levels of serotonin and dopamine were decreased in the recovery period after moderate endurance exercise than those recorded under the control condition. Thus, it suggested that the negative ion condition might affect the feeling of relaxation after endurance training. This study also found that the load on the maximum power set after a 10-min rest was significantly higher, and that negative ion effects reduced dopamine and serotonin during the rest which led to a more relaxed state. There is a possibility that the PNI condition might have affected the maximum power set results for the participants.

5. Conclusions

This study suggests that the PNI condition may have a positive effect on sports training. However, there are limitations to this study. We conducted the experiments on 10 elite swimmers, but it is necessary to expand the sample size in order to generalize this study. It is thus necessary that future studies be conducted with more participants. In addition, although this study conducted the experiment twice in an environment in which the athletes were randomly switched, it is recognized that emotions may change depending on the condition of the athlete on that day. Therefore, it is suggested that conducting a longitudinal experiment on the same participants might shed more accurate findings on the matter.

Author Contributions: Conceptualization, G.H. and H.M.; methodology, G.H., H.M., and T.T.; investigation, M.M., H.F., and T.T.; writing—original draft preparation, G.H.; writing—review and editing, H.M. and T.T. All authors have read and agreed to the published version of the manuscript.

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6

Comparative Biomechanical Analysis of the Hurdle Clearance Technique of Colin Jackson and Dayron Robles: Key Studies

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Abstract: The purpose of the study was to compare the biomechanical parameters of the hurdle clearance technique of the fifth hurdle in the 110 m hurdle race of Colin Jackson of Great Britain (12.91 s world record was set in 1994) and Dayron Robles of Cuba (12.87 s world record was set in 2008), two world record holders. Despite the athletes having performed at different times, we used comparable biomechanical diagnostic technology for both hurdlers. Biomechanical measurements for both were performed by the Laboratory for Movement Control of the Institute of Sport, Faculty of Sport in Ljubljana. A three-dimensional video analysis of the fifth hurdle clearance technique was used. High standards of biomechanical measurements were taken into account, thus ensuring the high objectivity of the obtained results. The following program was used: the ARIEL kinematic program (Ariel Dynamics Inc., Trabuco Canyon, CA, USA). The results of the comparative analysis found minimal differences between the two athletes, which was expected given their excellence. Dayron Robles's hurdle clearance was more effective, as it was characterized by a smaller loss of horizontal center of mass (COM) velocity. Robles's hurdle clearance took 0.50 s: 0.10 s for the take-off, 0.33 s for the flight phase, and 0.07 s for the landing phase. Colin Jackson completed the hurdle clearance slightly slower, as it took him 0.54 s. Jackson's take-off phase also lasted 0.10 s, his flight phase 0.36 s, and his landing 0.08 s. The two athletes are quite different in their morphological constitution. Dayron Robles is 10 cm taller than Colin Jackson, resulting in a lower flight parabola of CM during hurdle clearance of the Cuban athlete. Dayron Robles has a more effective hurdle clearance technique compared to Jackson's achievement. It can be considered that their individual techniques of overcoming the hurdle, reached their individual highest efficiency at this time.

Keywords: hurdling; biomechanics; hurdle clearance; technique analysis

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1. Introduction

The high hurdle race is one of the most technically demanding athletic events, and from a biomechanical standpoint, the hurdle race is a combination of a cyclic sprint and an acyclic clearance of ten 1.067 m high hurdles. According to Bruggemman [1], the high hurdle event can be divided into the following phases: approach run to the first hurdle, clearance of the hurdles and the rhythm between hurdles, and run-out from the last hurdle to the finishing line. Therefore, a proper hurdling technique is a complicated combination of various running and jumping kinematics [2]. Additionally the hurdler must show a high level of sprinting skill, excellent flexibility in the hip joint, coordination, balance, dynamic perception, elastic power, and a high level of technical knowledge [3,4]. Thus, athletes, coaches, and professionals are constantly looking for opportunities to improve the high hurdle performance, focusing on hurdling technique with particular emphasis on the kinematics and kinetics analysis. During the last three decades, there has been a considerable amount of references concerning the analysis of hurdling technique at different levels in order to improve performance [5–11].

One of the key elements that defines a competitive result in high hurdles is the hurdle clearance technique [11–17]. When clearing a hurdle, the loss of horizontal velocity should be minimized. This was confirmed by Amara et al. [17] and Coh et al. [18], who based on their hurdle clearance analyses, claimed that horizontal velocity is one of the most crucial factors, therefore losing it should be minimized; if not, the running time will be reduced. Additionally for the fastest possible and biomechanically effective clearance of the hurdle, the athlete's take-off distance and landing distance are essential. Furthermore, Salo and Grimshaw [19] determined the optimal ratio for an efficient hurdle clearance. The ratio applies to the dependency between the take-off of the trial leg and the landing of the lead leg and should be 60:40 in flight distance. The hurdle clearance depends on other factors, especially those that define the movement trajectory of the center of mass (COM). The correct positioning of these two points determines the optimal flight trajectory of the COM, which is reflected in the flight time, which should be as short as possible [5,9,12,20]. According to Coh et al. [18] and Bubaj et al. [21] these two situations is a prerequisite for an optimal flight path of the center of mass (COM). This optimal path results in a shorter flight time. In addition to the correct position, the kinematic–dynamic structure of the take-off and landing are important, as they directly affect the speed of hurdle clearance [7,10,16,22,23]. To sum up the above considerations after Lopez et al. [24], Li et al. [22], Park et al. [25], and Amara et al. [17], the main criteria of an optimal hurdle clearance technique include horizontal velocity, height of COM at take-off, velocity of the trail-leg, flight time, height of COM at landing, and contact time.

Over the years, with the development of technology, the ability to record and film competitions in track and field has increased significantly. There has been a considerable amount of biomechanical data concerning the kinematic analysis of hurdle races at a high level of performance such as the Olympic Games, World Championships, or international meetings [24–29]. These analyses of the specialized video recording are related to the technical aspects of single event observations where competition stress and adrenaline are imposed on athletes. There has been a limited number of studies where obtaining the kinematic parameters of 110-m male hurdlers on the basis of video techniques analyses has been carried out on two consecutive races with the same competitors–hurdlers. Therefore, researchers use various video recordings in their analyses, although sometimes there are methodological differences in data collection processes. A similar procedure was used for the analysis of hurdle races of Colin Jackson and Dayron Robles, who set high standards in this athletic discipline. They were both world record holders in their 110 m high hurdle race careers and won medals at every major international competition. Colin Jackson set the world record in the 60 m hurdle race in 1993 in Sindelfingen (Germany) with a time of 7.30 s. A year later, he improved the world record in the 110 m hurdles with a time of 12.91 s, still considered the seventh-best time in the history of this athletic discipline. Dayron Robles also improved the world record in the 110 m hurdle race (12.87 s) in 2008 in Ostrava (Czech Republic), which is considered to be the second-best result of all time in high hurdle races.

These studies were conducted to analyze comparable data held by the Laboratory for Movement Control of the Institute of Sport, Faculty of Sport in Ljubljana. Biomechanical measurements of both athletes were performed at different times, but under comparable conditions with similar measurement technologies. In both cases, a kinematic analysis of the fifth hurdle clearance technique was used. High standards of biomechanical measurements were taken into account, thus ensuring the high objectivity of the obtained results. We are aware that the study would have been even more valuable had we been able to analyze a greater number of obstacle clearances, but this was not possible due to organizational and technical constraints. The main aim of the study was to identify, analyze, and compare the essential kinematic parameters of the hurdle clearance technique at hurdle 5 of two athletes who have set the highest standards of biomechanical rationality of hurdle clearance in 110 m high hurdle races.

2. Materials and Methods

2.1. Participants

In this experiment, the participants were two world class hurdlers: Colin Jackson (body mass 75 kg, and height 182 cm) from Great Britain and Dayron Robles from Cuba (body mass 79 kg and height 191 cm). Both competitors specialized in 110 m hurdle, and were or are world record holders in 110 m hurdles. Some more personalized and anthropometric data of both athletes are shown in Table 1. The participants provided informed consent and were informed of the protocol and procedures for the study prior to the official video recording. The selection of athletes to conduct the experiment was specific and dependent on the possibility of making a video recording with its entire comprehensive procedure during an international meeting, and above all dependent on the level of participants in these competitions. Due to the fact that the experiment concerns the analysis of the hurdle technique for only two competitors, it can be qualified as a case study—the work reports scientifically sound experiments and provides a substantial amount of new information. The study was approved by the Human Ethics Committee of the University of Ljubljana.

Table 1. Basic anthropometric and biographical data of Colin Jackson (Great Britain) and Dayron Robles (Cuba).

Parameters	Colin Jackson	Dayron Robles
Date of birth	1967	1986
Body height (cm)	1.82	1.92
Body mass (kg)	75	79
Body Mass Index (BMI)	22.64	21.43
Best result (s)	12.91 *	12.87 **
Experimental result (s)	13.47	13.00
100 m best results (s)	10.29	10.71

BMI (Body Mass Index), * World Record in 1993, ** World record in 2008.

2.2. Experimental Design

The experiment design used was a comparison of dynamic and kinematic variables between two 110 m hurdles races at the segment between hurdles 4 and 5 and hurdle clearance of two world record holder. Both recordings of hurdles took place during regular international athletics competitions, although in two different places and two different years. These two conditions forced the experiment to match two different race recording methodologies. The hurdle races of Jackson and Robles were both recorded using two cameras each, although of different resolutions of 50 Hz frames per second and 100 Hz per second, respectively. From a methodological point of view, this may be a significant difference, but the conditions of variability were respected when processing data. In order to avoid the errors involved in analysis, real measurements were recalculated, taking into account the measurement error, which actually means that they corresponded (e.g., 50 Hz means 0.04 s between frames, so a hurdle clearance time of 0.5 s vs. 0.54 s represents a single frame). In both analyses the model of Dempster [30] was used for the calculation of the body's COM and the kinematic program ARIEL (Ariel Dynamics Inc., Trabuco Canyon, CA, USA) for the digitization was applied.

2.3. Procedure of Measurements—Colin Jackson

Colin Jackson's biomechanical analysis was carried out on 28 June 2002, at the International Meet in Velenje (EA Classic). His finish time was 13.47 s. The weather conditions were optimal; the outside temperature was 27 °C with a wind speed of + 0.2 m/s. Authorization to perform the experiment was approved by the Slovenian Track and Field Association. Biomechanical measurements were performed by a team of experts from the Laboratory for Movement Control of the Faculty of Sport in Ljubljana. Two synchronized cameras, namely Sony DSR-300-PK DVCAM Camcorders with Fujinon 17x lenses, were located at the main stands (the zone of hurdle 5) and operating at 50 Hz (shutter speed: 1/1000) were used to film the races. To record all kinematic parameters, the cameras were set at an angle of 120 to the direction of the moving hurdler in the segment between hurdles 4 and 5 (Figure 1). The zone of the 5th hurdle was calibrated with a calibration cube, one at the beginning of hurdle 4 and one at the end of hurdle 5. A 15-segment Dempster's model [30] and the ARIEL kinematic program (Ariel Dynamics Inc., Trabuco Canyon, CA, USA) were used to calculate the center of mass.

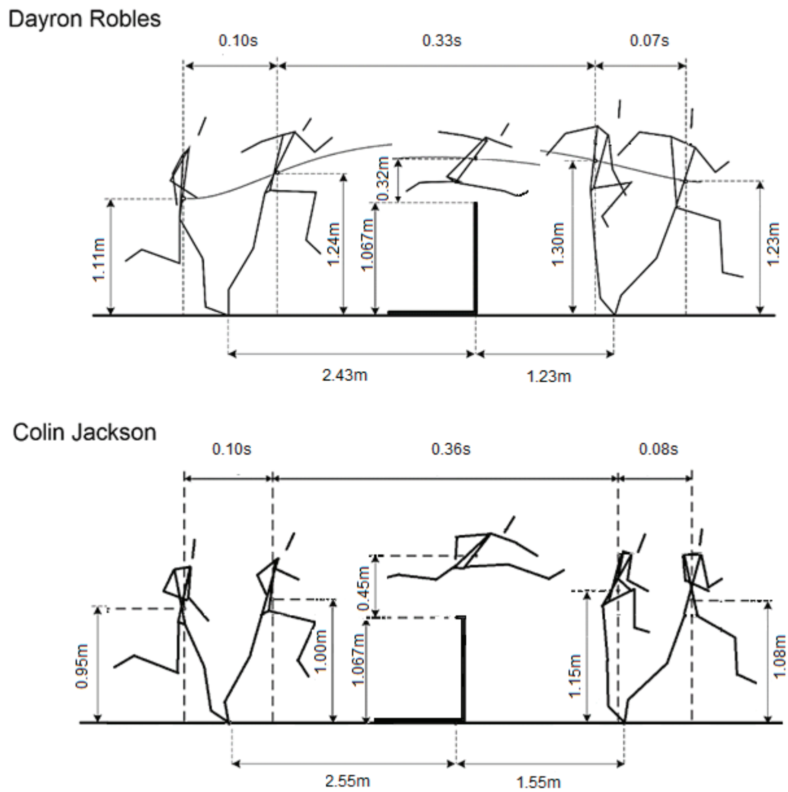

Figure 1. Comparison of biomechanical parameters of hurdle clearance.

2.4. Procedure of Measurements—Dayron Robles

Biomechanical analyses of Dayron Robles's 5th hurdle clearing technique was performed at the 2011 IAAF World Challenge—Zagreb International Race. Weather conditions were optimal; the outside temperature was 23 °C, and the wind speed was −0.2 m/s. Authorization to perform biomechanical measurements was obtained from the Technical Delegate of the European Athletics Federation and the Organizing Committee of the competition. The running track lane in the zone of the 5th hurdle was covered by two Casio high-frequency digital Casio EX-F1 512 × 384 (300 fps) sampled down to 100 fps cameras (Casio Computer Co., Ltd., Tokyo, Japan), which were interconnected and synchronized. The shutter speed of the Casio cameras was 1/300 s. The cameras were set perpendicular to the zone of the 5th hurdle (running hurdler) at an angle of 90°. The zone of the 5th hurdle was calibrated with a 2 m × 2 m × 2 m reference frame, within which eight points were measured. Data processing utilized an APAS computer system for 3D kinematic analysis (Ariel Performance Analysis System). Digitization of a 15-segment athlete body model was carried out, defined by 15 reference points [30] The point coordinates were smoothed with a 14 Hz digital filter. The center of mass (COM) was calculated from the digitized points based on Dempster's (1955) model of determination of COM via the ARIEL kinematic program (Ariel Dynamics Inc., Trabuco Canyon, CA, USA).

3. Results

The difference in body weight between competitors was only 4 kg. An even greater difference was in body height and was 10 cm in favor of Robles. Both measurements significantly differentiated hurdlers in terms of a measure of body fat (the ratio of the weight of the body in kilograms to the square of its height in meters), which was 1.21 in favor of Robles (Table 1). The time difference between those two world records is 0.04s. Jackson set his world record at the age of 26 and Robles at the age of 22. The age difference between competitors on the day of the experiment was approximately 10 years in favor of Jackson, and Robles obtained a better result by 0.47s in the 110 m performance.

Based on biomechanical analyses (Table 2), the following results were obtained: Robles's total stride length was 3.66 m, and the stride was completed in 0.33 s, while Jackson's stride length was 3.67 m, and it was slightly slower, lasting 0.36 s. During hurdle clearance, Dayron Robles reached the highest COM point at 1.38 m (0.32 m above the height of the hurdle), which corresponded to 72.2% of his body height. Colin Jackson reached the COM trajectory point at 1.52 m (0.45 m above the hurdle height), which was 83.4% of his height. The difference between the lowest COM point in the eccentric phase of the take-off was 1.11 m for Robles and 0.95 m for Jackson; and the highest COM point during the flight phase was 1.387 m for Robles and 1.517 m for Jackson. The height of the COM at the end of the concentric phase of take-off for Robles was 1.24 m and 1.08 m for Jackson.

Table 2. Biomechanical variables of the clearance of the fifth hurdle.

Variables	Colin Jackson	Dayron Robles	Difference	Δ (%)
Horizontal velocity 4 H–5 H (m/s)	9.14	9.18	0.04	0.43
Take-off (braking phase)				
Horizontal velocity of COM (m/s	8.81	8.70	0.11	1.25
Vertical velocity of COM m/s	–0.43	–0.70	0.37	62.79
Velocity resultant of COM (m/s	8.82	8.73	0.09	1.03
Height of COM (m)	0.95	1.11	0.16	16.84
Foot to hurdle distance (m)	2.09	2.43	0.34	16.26
Take-off (propulsion phase)				
Horizontal velocity of COM (m/s)	9.11	9.00	0.11	1.21
Vertical velocity of COM (m/s)	2.35	1.80	0.55	23.41
Velocity resultant of COM (m/s)	9.41	9.18	0.23	2.45
Height of COM (m)	1.08	1.24	0.16	14.81
Push-off angle (°)	72.9	78.7	5.80	7.95
Contact time (s)	0.10	0.10	0.0	0.0
Flight				
Flight time (s)	0.36	0.33	0.03	8.34
Height of COM above the hurdle (m)	0.45	0.32	0.13	28.89
Maximal height COM (m)	1.44	1.52	0.08	5.55
Landing (braking phase)				
Horizontal velocity of COM m/s	8.77	8.80	0.03	0.34
Vertical velocity of COM (m/s)	–1.02	–1.00	–0.02	1.97
Velocity resultant of COM (m/s)	8.84	8.86	0.02	0.22
Height of COM (m)	1.15	1.30	0.15	13.04
Foot to hurdle distance (m)	1.58	1.23	0.35	22.16
Landing (propulsion phase)				
Horizontal velocity of COM (m/s)	8.41	9.35	1.06	11.17
Vertical velocity of COM (m/s)	–1.32	–1.00	–0.32	24.25
Velocity resultant of COM (m/s)	8.53	9.40	1.13	10.19
Height of COM (m)	1.06	1.23	0.17	16.03
Contact time (s)	0.08	0.07	0.01	12.50

4. Discussion

The entire process of hurdle clearance took 0.50 s for Robles; it took 0.10 s for take-off, 0.33 s for the flight phase, and 0.07 s for the landing phase. Meanwhile, Colin Jackson completed the hurdle clearance a little more slowly, as it took him 0.54 s. Jackson also spent 0.10 s for take-off, 0.36 s for the flight phase, and 0.08 s for the landing phase. For comparison, the measurement of Amara [23]—a medium level athlete (13.90 s at 110 m hurdles) showed differences in the abovementioned parameters of 0.60 s, 0.36 s, 0.21 s, and 0.12 s (respectively for each variable). Jackson's slower clearance of the hurdle is associated with a higher rise in his COM above the hurdle and a longer landing distance over the hurdle, extending both the flight phase and the shock absorption phase. A slower hurdler [30] had a similar problem; his excessive height of the vertical COM displacement together with a high take-off angle had a negative impact on the time to clear the hurdle. The difference in the flight parabola between the two athletes can be attributed mainly to the difference in their height and the difference in their functional abilities. Based on the kinematic parameters of the parabola, we can, therefore, conclude that Dayron Robles has a more rational hurdle clearance technique (Figure 1).

The take-off distance for Robles was 2.43 m, which was 66.4% of the total clearance length over the hurdle. For Jackson, the take-off distance was 2.09 m, which was 57.0% of the total length of clearance. Jackson's landing distance was 1.58 m (43.0% of his total stride length), while Robles's was 1.23 m (33.6% of his total stride length). It can be compared with some other studies [10,30], which indicate that the optimal ratio between take-off spot and landing place should be 40–60%, which is comparable with Amara's [17] findings (i.e., 58:42). This ratio was confirmed by previous researchers [8,18,24,28,31,32], which indicated that take-off distance should range from 2.04 cm to 2.31 cm. In turn, the landing distance was shorter. We can identify two different hurdle clearance strategies. Robles has a faster hurdle clearance; his take-off is elongated, and his landing is closer to the hurdle. The duration of Robles's flight phase is 0.33 s, and that of Jackson is 0.36 s. A technical model of When [33] indicated that the optimal over the hurdle time should range between 0.30 and 0.33 s for a world class hurdler. This confirms the importance of the take-off (the angle between the top of the foot and the hip) and landing distances in high hurdler races, as was previously mentioned by Coh and Iskra [31] and Lopez at el. [24].

In the concentric phase, Robles had a take-off angle of 78.7 °, and Jackson's was 72.9 °. The COM velocity resultant during the braking phase of the take-off was 8.73 m/s for Robles and 8.82 m/s for Jackson. This velocity resultant of COM is defined as the vector sum of the vertical COM velocity (0.70 m/s for Robles, –0.43 m/s for Jackson) and horizontal COM velocity (8.70 m/s for Robles and 8.81 m/s for Jackson). It changes until the last contact of the take-off when it measured 9.18 m/s for Robles and 9.41 m/s for Jackson. Robles's vertical COM velocity at that time was 1.80 m/s, and Jackson's was 2.35 m/s; their horizontal COM velocities were 9.00 m/s and 9.11 m/s, respectively. The COM horizontal velocity during take-off thus increased by 0.30 m/s for both Robles and Jackson. The relative increase in the horizontal velocity of COM for Robles was 3.30% and 3.29% for Jackson (Figure 2). For both athletes, the duration of their take-off was the same. Robles's COM height during take-off increased by 0.13 m, equal to Jackson's (Figure 1). It is comparable with data of Amara [17], Li and Fu [34], and Lopez at el. [24], who claimed that during take-off (propulsion phase), the average height of the COM should be around 1.12 m.

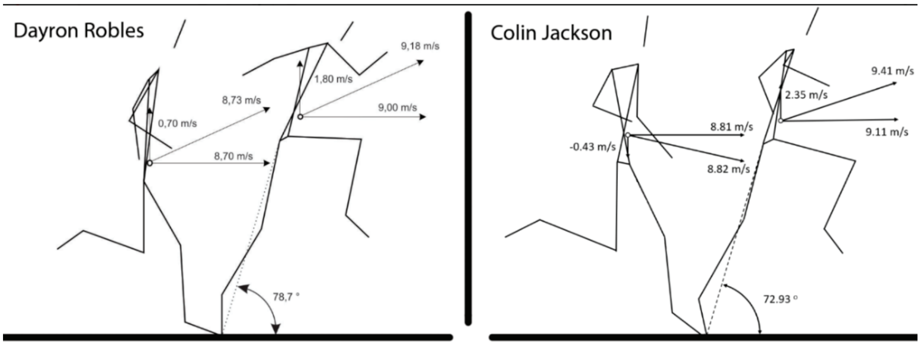

Figure 2. Comparison of the biomechanical parameters of take-off before the hurdle.

The transition between hurdle clearance and the sprint between hurdles is dependent on the landing phase. For Robles, the horizontal velocity at landing was 8.80 m/s, which means that the horizontal velocity decreased by 0.20 m/s (2.2%). For Jackson, the horizontal velocity decreased by 0.34 m/s (3.7%). During the landing phase, Robles's height of COM decreased by 0.07 m (5.4%) and 0.09 m (7.8%) for Jackson. The short duration of the landing phase (0.07 s for Robles and 0.08 s for Jackson) indicated a high level of reactive power [35] for both athletes (Figure 3), and an efficient transition to sprinting between hurdles [4,36].

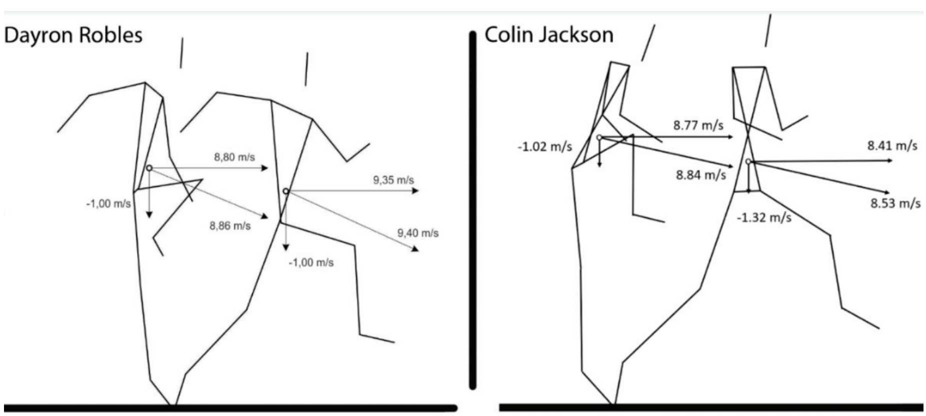

Figure 3. Comparison of the biomechanical parameters of the landing.

For Jackson, the reduction in the horizontal velocity of COM was greater than that of Robles, and the height of his center of mass (COM) was lower at landing, so it can be concluded that Robles has a slightly more biomechanically rational hurdle clearance technique. In addition, our results do not contradict the research of Amara [23], who claimed that the vertical component of COM velocity and the lead-leg/trail-leg at take-off and at flight phase constituted key factors of optimum hurdle clearance. According to Amara [17,23] and Shibayama et al. [37], in addition to the take-off angle, the knee and the hip angles are very important in high hurdles clearance, as also found in previous studies done by Coh [18,38], Xi et al. [22], Bubaj [21] and Sidhu [39]. Liu [40] just confirmed this statement and additionally indicated that the flight-phase duration is also defined by the takeoff angle, which should be lower.

5. Conclusions

In the present study, we analyzed the rationality of the 110 m hurdle clearance technique of Colin Jackson and Dayron Robles, using diagnostic technology for kinematic analysis. Both athletes have roughly the same personal record in the 110 m hurdle races (Jackson 12.91 s, Robles 12.87 s). The two hurdlers are quite different in morphological constitution, with Dayron Robles being 10 cm taller than Colin Jackson. Based on the results obtained, it can be concluded that Dayron Robles has a more effective hurdle clearance technique. It is characterized by a smaller loss of horizontal velocity of COM during clearance, a better COM flight parabola over the hurdle, and a smaller difference between the hurdle height and the height of the highest COM point, compared to Jackson's achievement. It proves that their hurdle clearance efficiencies differ but depend on the same kinematic parameters. Therefore, it can be considered that their individual technique of overcoming the hurdle their reached individual highest efficiency at this time. On this basis, we can also assume that the difference in overcoming one hurdle (the fifth) accumulated in the remaining hurdles until the end of the race, which reflects the final results of the races. Here Robles obtained a better running time in the 110 m hurdles.

6. Practical Application

From a practical point of view, based on some of the spatiotemporal parameters presented in the present analysis, there are some high hurdle common performance indicators. In order to optimize high hurdle performance with special regard to clearance hurdle movement performance, lower vertical displacement of COM, combined with right angle of take-off and short contact-time at the take-off and landing phases must be considered. These elements help improve a quick turn between horizontal and vertical velocity of forward propulsion and fast return of the trail leg at landing. To improve these indicators, appropriate training needs to be applied. It should consider high technical proficiency training and first of all activities which improve a higher rate of force development.

Author Contributions: Conceptualization, M.Č. and K.M.; Data curation, S.Š. and K.M.; Formal analysis, M.Č., N.B., S.Š. and K.M.; Investigation, M.Č., N.B. and S.Š.; Methodology, M.Č., N.B., S.Š. and K.M.; Resources, M.Č.; Software, N.B. and S.Š.; Supervision, M.Č. and K.M.; Validation, M.Č. and N.B.; Writing–original draft, M.Č., N.B. and K.M.; Writing–review & editing, M.Č. and K.M. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The authors would like to acknowledge the involvement of the participants for their contribution to this study.

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Lower Back Complaints in Adolescent Competitive Alpine Skiers: A Cross-Sectional Study

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Abstract: Background: Little is known about lower back complaints in adolescent competitive alpine skiers. This study assessed their prevalence and severity (i.e., intensity and disability) with respect to sex, category, discipline preference, and training attributes. Methods: 188 competitive skiers aged 15 to 18 years volunteered in this study. Data collection included (i) questions on participants' demographics, sports exposure, discipline preferences, and other sports-related practices; (ii) the Nordic Musculoskeletal Questionnaire on lower back complaints; and (iii) the Graded Chronic Pain Scale. Results: As many as 80.3% and 50.0% of all skiers suffered from lower back complaints during the last 12 months and 7 days, respectively. A total of 50.7% reported their complaints to be attributable to slalom skiing, and 26% to giant slalom. The majority of complaints were classified as low intensity/low disability (Grade I, 57.4%) and high intensity/low disability complaints (Grade II, 21.8%). The Characteristic Pain Intensity was found to be significantly related to the skiers' years of sports participation, number of competitions/season, and number of skiing days/season. Conclusion: This study further supports the relatively high magnitudes of lower back-related pain in adolescent competitive alpine skiers, with a considerable amount of high intensity (but low disability) complaints, and training attributes being a key driver.

Keywords: alpine skiing; athletes' health; epidemiology; spine; musculoskeletal injuries

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1. Introduction

Competitive alpine skiing is a popular yet high-risk sport. At all competition levels, health problems are frequent [1–7]. In particular, lower back has been reported to be one of the most affected body regions for overuse complaints [8]. Adolescent competitive alpine skiers are also known to suffer from relatively high rates of radiographic abnormalities in the thoracolumbar spine [9]. Specifically, degenerative disc changes were observed to be more prevalent in adolescent competitive alpine skiers than in age-matched controls [10]. Moreover, a recent study found such disc degenerations (particularly disc dehydration and disc protrusion) to be significantly more prevalent in symptomatic than in asymptomatic athletes [11]. However, little is known about the prevalence of lower back complaints in adolescent skiers with respect to severity (i.e., intensity and disability). Additionally, the role of discipline preference is widely unexplored as of yet.

The link between lower back pain and physical activity has been described as a U-shaped relationship, whereas increased risk was found for both sedentary subjects and those practicing strenuous physical activities [12]. According to this association, athletes may be considered a high-risk population, mainly due to the training and competition loads they are subjected to. Moreover, as a result of their musculoskeletal and spinal immaturity and excessive height growth, adolescent athletes are especially vulnerable [11,13].

From a biomechanical perspective, the following factors may contribute to overloading of the lower back structures in alpine ski racing [14]: (a) repetitive and heavy mechanical loads, particularly when accompanied by insufficient recovery between the training sessions [15]; (b) unphysiological postures (i.e., frontal bending, lateral bending, and torsion), associated with high ground reaction forces (up to 2.89 times the body weight) [16]; and (c) excessive exposure to low-frequency whole-body vibrations [17–20]. Since all of these factors are typical characteristics of alpine skiing-specific sports exposure, studying the relations between training attributes and lower back complaints is of superior importance.

Therefore, the aims of this study were: (1) to describe the demographics, sports exposure, and other sports- or warm-up-related practices of adolescent competitive alpine skiers; (2) to assess the prevalence of lower back complaints in this specific cohort with respect to sex, category, and discipline preference; (3) to explore their lower back complaints severity (i.e., intensity and disability); and (4) to investigate the potential relations with training attributes.

2. Materials and Methods

2.1. Study Design and Setting

This study was designed as a cross-sectional observation and was based on a structured and customized questionnaire package. Data were collected in the participants' sport clubs facilities at the end of the competition season. Questionnaires were spread physically. A member of the research team introduced the questionnaires to the participants, explaining all the questionnaire items and scales. Subsequently, the participants filled the questionnaires independently and individually.

2.2. Participants and Recruitment

Participants were included if they were members of ski clubs associated with the FISI (Italian Winter Sports Federation) Veneto region section and competed in the categories under 16 (U-16) and under 18 (U-18) years old. There were no study exclusions. All the ski clubs associated with the FISI Veneto region were contacted and invited to take part in the study. Finally, 188 adolescent competitive alpine skiers (110 males and 78 females) volunteered for the purpose of the current study; 128 belonged to the category U-16 and 60 to the U-18. The entire study sample represented about 70% of all U-16 and U-18 competitive alpine skiers affiliated to the FISI clubs in that region. The Ethics Committee of the Department of Biomedical Sciences of the University of Padua approved the study (HEC-DSB/02-19). Prior to the study, all the participants and their parents or legal representatives provided written informed consent. The participants did not receive any reward for their participation in the study.

2.3. Assessment Methods and Parameters

The questionnaire package comprised four parts: (1) questions on participants' demographics, sports exposure (years of sports participation, number of competitions/season, number of skiing days/season, number of athletic preparation days/season) and other sports- or warm-up-related practices; (2) the Nordic Musculoskeletal Questionnaire (NMQ), Italian version [21,22]; (3) specific questions on how their skiing discipline (e.g., Slalom—SL; Giant Slalom—GS; Super-G—SG;

or Downhill (DH)) was related to the occurrence of lower back complaints; (4) the Graded Chronic Pain Scale (GCPS), Italian version [23,24].

The NMQ aimed on investigating the time prevalence of musculoskeletal complaints in the lower back during the last 12 months and 7 days, respectively, as well as on whether these complaints resulted in any restrictions while carrying out normal activities or whether they required medical attention or not. Questionnaire completion was supported by a body map displaying the pain area. The GCPS was used to grade the severity of the lower back complaints. The underlying methodology consists of seven questions related to pain intensity items and disability items with respect to the 6 months preceding the questionnaire. Answers were provided on a scale from 0 (e.g., "no pain" or "no interference/change") to 10 (e.g., "pain as bad it could be" or "unable to carry on any activity/extreme change") [23]. Based on these scale points, as well as on a specific scoring system, the Characteristic Pain Intensity (0–100), Disability Score (0–100), and Disability Points (0–3) were calculated and, subsequently, were assigned to five severity grades, as described in Von Korff et al. [23]: Grade 0 (pain-free); Grade I (low disability—low intensity); Grade II (low disability, high intensity); Grade III (high disability, moderately limiting); and Grade IV (high disability—severely limiting).

2.4. Statistical Analysis

Participant demographics, sports exposure, and training/competition/other sports practices were expressed as the mean ± SD and percentage proportions, respectively. NMQ-related measures and GCPS-based classifications were expressed as the absolute number and percentage of participants affected. The GCPS scores were described as the mean ± SD. All the measures were presented for the entire sample and the subgroups based on sex (female and male) and competition category (U-16 and U-18). Prevalence was additionally described with respect to the discipline to which they were perceived as being attributable. Pearson's Chi-squared tests were used to assess the potential sex and category differences in measures with percentage proportions at $p < 0.05$. Independent sample t-tests were used to evaluate the sex and category differences in interval scaled measures at $p < 0.05$. Pearson's correlation analysis was performed on GCPS items and scores, as well as on the relationship between GCPS scores, years of sports participation, number of competitions/season, number of skiing days/season, and number of athletic preparation days/season. For any correlation analysis, statistical significance was set at $p \leq 0.05$.

3. Results

3.1. Participant Demographics, Sports Exposure and Training/Competition/Other Sports Practices

Male participants were characterized as follows: age: 16.1 ± 1.1 y; weight: 65 ± 10 kg; height: 1.74 ± 0.08 m; BMI: 21.5 ± 2.3 kg/m^2; years of sports participation: 8.1 ± 2.4 y. The group of female participants had the following characteristics: age: 16 ± 1 years; weight: 56.2 ± 6.4 kg; height: 1.65 ± 0.05 m; BMI: 20.7 ± 1.9 kg/m^2; years of sports participation: 7.1 ± 2.9 y. Over the past competition (i.e., winter) season, the participants reported a mean of 85.4 ± 47.2 days (3.5 ± 1.3 days/week) of ski training and participated in 17.2 ± 12.0 competitions on average. Independent sample t-tests revealed no significant differences between the sexes. However, there were significant differences in the number of skiing days/season (t (186) = 2.18, $p = 0.029$) and the number of competitions in the last season (t (186) = 7.22, $p < 0.001$) between the U-16 and U-18 categories, with athletes in the U-18 category who performed more skiing days and competitions. Most participants (62.8%) declared that they practiced one or more sports other than alpine skiing, 83.5% reported that they participated in specific athletic preparation programs, and 78.3% declared that they regularly warm-up before skiing. The Chi-squared tests revealed, however, no significant sex or category differences in these variables at $p < 0.05$.

3.2. Prevalence of Lower Back Complaints

An overview of the NMQ-related results is presented in Table 1. A total of 80.3% of all participants reported having suffered from lower back complaints during the last 12 months, and 50.0% during the last 7 days. As many as 28.2% reported that they have been restricted in normal activities (e.g., job and leisure activities) during the last 12 months, and 27.7% indicated that their lower back complaints required medical attention during the last 12 months. Except for lower back complaints during the last 7 seven days, which were more frequent in females, there were found no sex or category differences. Interestingly, 50.7% of the participants reported their lower back complaints being attributed to performing SL, 26.0% to GS, and 7.3% to SG; meanwhile, no participants attributed their lower back complaints to DH skiing. A remarkable season period-related difference in the frequency patterns of lower back complaints was found between the competition period and the off-season period. During the off-season period, only 3.3% reported their lower back complaints to last longer than two weeks, while during the competition period this percentage proportion was more than six times higher (21.3%).

Table 1. Overview of the Nordic Musculoskeletal Questionnaire (NMQ)-based results and differences between sexes and categories.

NMQ Measure	Overall $n = 188$	Male $n = 110$	Female $n = 78$	χ^2(df), p	U-16 $n = 128$	U-18 $n = 60$	χ^2(df), p
Lower back complaints during the last 12 months	(151) 80.3%	(89) 80.9%	(62) 79.5%	n.s.	(103) 80.5%	(48) 80%	n.s.
Lower back complaints during the last 7 days	(94) 50%	(42) 42.7%	(47) 60.3%	5.61(1) 0.018	(65) 50.8%	(29) 48.3%	n.s.
Restricted in normal activities during the last 12 months	(53) 28.2%	(31) 28.2%	(22) 28.2%	n.s.	(36) 28.1%	(17) 28.3%	n.s.
Required medical attention during the last 12 months	(52) 27.7%	(33) 30%	(19) 24.4%	n.s.	(35) 27.3%	(17) 28.3%	n.s.

All NMQ-related measures are expressed as absolute numbers and the percentage proportion on the overall group/subgroups (number of affected skiers/number of skiers per group × 100). Levels of significance for sex and category differences are based on Pearson chi-square tests. n.s.: not significant at $p < 0.05$; U-16: under 16 years; U-18: under 18 years.

3.3. Severity of Lower Back Complaints

The GCPS-related results are summarized in Table 2. The mean value of Characteristic Pain Intensity was 37.53 ± 18.0 and the Disability Score was 13.27 ± 14.59 on average. There were no significant sex or category differences at $p < 0.05$. Most participants (57.4%) suffered from low intensity—low disability complaints (Grade I), and 21.8% from high intensity—low disability complaints (Grade II). Again, there were no significant differences between males and females, or between U-16 and U-18 skiers.

Table 2. Overview of the Graded Chronic Pain Scale (GCPS) scores and differences between sexes and categories.

GCPS Score	**Overall** $n = 188$	**Male** $n = 110$	**Female** $n = 78$	**t(df), *p***	**U-16** $n = 128$	**U-18** $n = 60$	**t(df), *p***
Characteristic Pain Intensity	37.53 ± 18.0	28.30 ± 21.98	32.26 ± 22.11	n.s.	30.62 ± 22.71	28.50 ± 20.70	n.s.
Disability Score	13.27 ±14.59	11.29 ±15.22	9.61 ±12.32	n.s	11.51 ±15.06	8.64 ±11.59	n.s
GCPS Classification				$\chi 2$			$\chi 2$
Grade 0 Pain free	(39) 20.7%	(23) 20.9%	(16) 20.5%	n.s.	(27) 21.1%	(12) 20%	n.s.
Grade I Low intensity-Low disability	(108) 57.4%	(64) 58.2%	(44) 56.4%	n.s.	(70) 54.7%	(38) 63.3%	n.s.
Grade II High intensity-Low disability	(41) 21.8%	(23) 20.9%	(18) 23.1%	n.s.	(31) 24.2%	(10) 16.7%	n.s
Grade III High Disability-Moderately Limiting	—	—	—	—	—	—	—
Grade IV High Disability-Severely Limiting	—	—	—	—	—	—	—

GCPS scores are expressed as mean ± SD. GCPS classifications are expressed as absolute numbers and the percentage proportion of the overall group/subgroups (number of affected skiers/number of skiers per group × 100). Levels of significance for sex and category differences are based on independent sample *t*-tests and Pearson chi-square tests, respectively. n.s.: not significant at $p < 0.05$; U-16: under 16 years; U-18: under 18 years.

3.4. Relationship between Different Severity Measures, as well as between Severity and Training Attributes

We found a medium-correlation Characteristic Pain Intensity and Disability Score (r = 0.62, $p < 0.01$). Moreover, the average lower back complaint intensity, as well as the intensity at the time of filling out the questionnaire, positively correlated with the worst pain intensity experienced within the last 6 months (r = 0.63, $p < 0.01$; r = 0.47, $p < 0.01$, respectively).

The results of the correlation analysis between the GCPS scores and different training attributes are highlighted in Table 3. There were small yet significant correlations between the Characteristic Pain Intensity and the training attributes "years of sports participation", "number of competitions/season", and "number of skiing days/season". Moreover, an additional independent *t*-test showed a significant difference (t (186) = 2.12, $p = 0.035$, d = 0.31) in the lower back complaint severity (i.e., GCPS—Characteristic Pain Intensity) between skiers who exclusively practiced alpine skiing and those who also practiced other sports, with the first group reporting higher intensities.

Table 3. Correlation between the Grading Chronic Pain Scale scores and questions on sports exposure.

	Characteristic Pain Intensity	Disability Score
Years of sports participation	0.28 **	0.15 *
Number of competitions/season	0.21 **	−0.02
Number of skiing days/season	0.27 **	0.12
Number of athletic preparation days/season	0.03	−0.09

Level of significance based on Pearson correlation analysis: * $p < 0.05$, ** $p < 0.01$.

4. Discussion

The main findings of this study were: (1) as many as 80.3% of all participating adolescent skiers suffered from lower back complaints during the last 12 months (50.0% during the last 7 days; 28.2% with restrictions in normal activities; and 27.7% requiring medical attention); (2) 50.7% of the participants reported their lower back complaints being attributable to SL, and 26.0% to GS; (3) despite the fact that the majority of the participants experienced lower back complaints of a low intensity/low disability (Grade I, 57.4%), a considerable portion suffered from a high intensity/low disability complaints (Grade II, 21.8%); (4) there were small yet significant correlations between the Characteristic Pain Intensity and the training attributes "years of sports participation", "number of competitions/season", and "number of skiing days/season".

4.1. Prevalence of Lower Back Complaints with Respect to Sex, Category and Discipline Preference

The current study found relatively high rates of lower back complaints in adolescent competitive alpine skiers. Indeed, 50.0% and 80.3% of the participants displayed lower back complaints in the last 7 days and 12 months, respectively. These values are considerably higher than those was previously reported for other populations. For example, a 12 months lower back pain prevalence of between 49.8% and 65.0% was observed in previous studies in elite athletes of different sports [25–27]. A 7 days lower back pain prevalence between 19.4% and 25.3% was reported for endurance athletes [25]. Previous works found a 12 months lower back complaints prevalence ranging from 20.5% to 57.0% in non-athletic adolescents [25,28,29], while a 7 days lower back complaints prevalence of about 20.0% was reported for young non-athletes [25].

The higher prevalence of lower back complaints observed in the present study compared to other athletic (and non-athletic) adolescents suggests that competitive alpine skiers are especially prone for lower back complaints. Indeed, in the sport of alpine ski racing, repetitive and heavy mechanical loads, high ground reaction forces, and the exposure to low-frequency whole-body vibrations have been shown to adversely affect the spinal structures while skiing [14,16,17]. Moreover, in young skiers, the immaturity of the musculoskeletal system may exacerbate the damage experienced by the spine during the practice of this sport [13].

Despite these plausible sports-related adverse loading patterns, only a few studies, however, have investigated the occurrence of lower back complaints in competitive alpine skiers. Moreover, due to focusing on a different age group and reporting other time prevalence measures or absolute injury rates, most of them are not directly comparable to the results of the current study [3,4,6,8,11]. The only study directly comparable to our investigation reported similar magnitudes of current low back pain (67.0%) in ski high school athletes aged 15–19 years [30].

Noteworthy, in our study, a higher 7 days lower back complaints prevalence was observed in females with respect to males (60.3% vs. 42.7%). These results are in agreement with previous works and, on the one hand, may be explained by a different pain threshold and symptom perception between males and females [31,32]. On the other hand, this sex difference may also be explained by the different anatomical characteristics of the female body (e.g., greater spine flexibility), as well as the different pubertal growth and hormonal states [33,34].

Furthermore, our study revealed that, during the 12 months prior to data collection, 28.2% of the participants were restricted in carrying out normal daily life activities, while 27.2% needed to see a physician. This latter percentage is similar to the magnitudes found in previous studies (range between 24.0 and 33.0%) including large cohorts of children and adolescents [35,36].

Interestingly, we found different skiing disciplines to have different perceived impacts on lower back complaints. Indeed, 50.7% attributed their lower back complaints to SL, while 26.0% reported to have suffered them in connection with GS and 7.3% with SG. None of the participants attributed their lower back complaints to DH. A possible explanation is that, in SL, there are more pronounced and larger ground reaction force peaks (approximately plus 20.0%) after gate passage than in GS [37].

Regarding the prevalence of lower back complaints according to the annual programming period, we found that the prevalence of lower back complaints lasting less than 7 days was 86.0% in the off-season and 33.3% in the competition season. Conversely, the frequency of lower back complaints lasting more than two weeks changed from 3.3% in the off-season to 21.3% in the period of the competition season. This fact may suggest that more severe lower back complaints emerge from skiing rather than from off-snow training [3].

4.2. Severity of Lower Back Complaints with Respect to Intensity and Disability

Another aim of this work was to study the severity (i.e., pain intensity and disability) of lower back complaints in adolescent competitive alpine skiers. Despite the fact that most of the participants (57.4%) reported low intensity—low disability complaints (Grade I of the GCPS), 21.8% showed high intensity—low disability complaints (Grade II). These findings showed that a considerable part of the participants suffered from a relatively high severity of lower back complaints already at a relatively young age (15–18 y). However, the pain resulted in being of low disability, which is in agreement with previous studies in adolescent athletes [25,38]. One potential explanation for this finding may be the consideration that the cohort of the current study consisted of relatively young athletes, who may not have suffered from an extensive accumulation of adverse loadings over time yet.

4.3. Relationship between Lower Back Complaints Severity and Training Attributes

The current study revealed small yet significant correlations between Characteristic Pain Intensity and the training attributes "years of sports participation", "number of competitions/season", and "number of skiing days/season". These findings further support our current understanding of the development of lower back overuse injuries, according to which an accumulation of adverse loadings on the athletes' spine is a key driver for inducing pain [16]. However, the present sample was homogeneous with respect to training attributes, since the participants of our study belonged to ski clubs of the same region. Therefore, the results of this study may be specific to our cohort and should be interpreted with caution.

4.4. Methodological Considerations

Despite providing valuable new insights into the prevalence and severity of lower back complaints in adolescent competitive alpine skiers, this study has some limitations that one should be aware of. First, the retrospective nature of the NMQ and GCPS methodologies may cause them to suffer from a recall bias. Recent and more severe complaints are more likely to be remembered than older and less severe ones. Second, the background and experience of the participants filling out the questionnaires may influence the outcomes. Third, other potential cofounders for lower back complaints, such as smoking, hours of sleep per night, and psychosocial factors (depression, stress, poor academic performance, poor competitive results, etc.), were not evaluated in this study.

5. Conclusions

This study provides a new set of data regarding the prevalence and severity of lower back complaints in a sample of adolescent competitive alpine racers. It further supports the relatively high magnitudes of lower back-related pain, with a considerable amount of high intensity but low disability complaints. Interestingly, more low back complains were reported during SL and GS than other skiing disciplines. Moreover, this study further highlights an accumulation of adverse loadings on the athletes' spine being a key driver for developing pain conditions. Accordingly, adolescent competitive alpine skiers should be particularly protected by rigorous prevention strategies already before reaching adolescence.

Author Contributions: Conceptualization, A.C., D.S., and S.M.; investigation, M.G.; resources, D.S. and M.G.; data curation, A.C., F.S., and M.G.; writing—original draft preparation, F.S., M.G. and J.S.; writing—review and editing A.C., J.S., and S.M. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The authors would like to thank the participants for their kind participation and their coaches, ski clubs, and the FISI Veneto Committee for supporting and facilitating the completion of this study.

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Ankle Taping Effectiveness for the Decreasing Dorsiflexion Range of Motion in Elite Soccer and Basketball Players U18 in a Single Training Session: A Cross-Sectional Pilot Study

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Abstract: Ankle sprains have been defined as the most common injury in sports. The aim of the present study was to investigate the ankle taping for the reduction of ankle dorsiflexion range of motion (ROM) and inter-limb in elite soccer and basketball players U18 in a single training session. Methods: A cross-sectional pilot study was performed on 38 male healthy elite athletes divided into two groups: a soccer group and a basketball group. Ankle dorsiflexion ROM and inter-limb asymmetries in a weight-bearing lunge position were assessed in three points: with no-tape, before the practice and immediately after the practice. Results: For the soccer group, significant differences ($p < 0.05$) were observed for the right ankle, but no differences for the asymmetry variable. The basketball group reported significant differences ($p < 0.05$) for the right ankle and symmetry. Conclusions: Ankle taping decreased the ankle dorsiflexion ROM in youth elite soccer and basketball players U18. These results could be useful as a prophylactic approach for ankle sprain injury prevention. However, the ankle ROM restriction between individuals without taping and individuals immediately assessed when the tape was removed after the training was very low.

Keywords: ankle sprain; taping; range of motion; soccer; basketball; prevention; musculoskeletal disorders; personalized treatment

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1. Introduction

Ankle sprains have been defined as the most common injury in sports [1]. Worldwide, soccer and basketball are some of the most popular sports for both participation and viewing. These athletes reported the highest injury incidence ratios [2,3]. Elite soccer players experienced between 13 and 55 injuries per 1000 competitive hours. In addition, the lower limb is most commonly affected as foot, and ankle injuries were the most prevalent diagnoses in training or competition [4]. Regarding the basketball athletes, McKay et al. reported an ankle incidence rate of 3.85 per 1000 participations, landings being the most prevalent mechanism of injury [5]. Most cases of ankle sprain in basketball and soccer players occurred when the foot takes an over-plantar-flexed position during running or landing after a jump [6]. In addition, amateur and youth soccer players have a higher risk of suffering a lateral ankle sprain than professional players due to an increase of strength and training experience for the professional players [7].

Functional approaches, including prophylactic methods such as taping, bandaging, or bracing of the ankle to protect the ankle ligaments have been studied, with the aim of reducing the incidence rates of ankle sprain injuries since the 1990s [8].

In the past decade, several studies have been developed to assess the effectiveness of ankle taping for the protection of the ankle ligaments in maximal stress situations, such as an ankle sprain [9]. Ankle taping was associated with competition, rehabilitation, and prevention sport contexts over many years. Karlsson and Andreasson reported a restricted range of motion (ROM) for the ankle joint in individuals with ankle taping but with a decrease in the peroneus muscle reaction time assessed by electromyography [10]. Taping with or without pre-wrap has also been studied, i.e., Ricard et al. reported the effectiveness of the ankle taping to reduce the average inversion velocity, maximum inversion velocity, and time to maximum inversion velocity, but no differences between individuals with or without pre-wrap were observed [11]. Pederson et al. argued that ankle taping was effective in the reduction of inversion movement in a study carried out in rugby players. In addition, authors have also reported that there may be a functional restriction on inversion parameters after exercise with ankle taping [12]. Callaghan reported that the inversion-eversion ROM had been limited by up to 41% as ankle taping in a non-weight bearing position presented as a restriction of the frontal plane movements [13]. Kemler et al. reported in a systematic review that elastic bandages and ankle taping were effective for the ankle sprain episodes [14]. Kerkhoffs et al. conducted a systematic review regarding the different bandage approaches for ankle sprain situations, and they concluded that the taping method is effective to limit the ankle ROM. However, several complications have been observed, such as skin irritations and a longer time to return to work when compared with an elastic bandage [15]. Jeffries et al. reported that ankle taping should provide protection to the ankle joint without affecting the planned change-of-direction or reactive agility performance in basketball players [16].

Currently, research showed that ankle taping is often employed in elite sports in order to prevent the incidence and severity of lateral ankle sprains. Thus, the aim of the present study was to investigate in elite soccer and basketball players U18 the effectiveness of ankle taping in the reduction of ankle dorsiflexion ROM and inter-limb asymmetries throughout the training session. Thus, we assessed the ankle dorsiflexion ROM in a weight-bearing lunge position in three time-points: (1) with no-tape, (2) before the practice, and (3) immediately after the practice. Prior research concluded that the ankle taping would reduce the ankle joint dorsiflexion angle immediately after the taping. However, we hypothesized that the taping had lost the initial effectiveness for restricting the ankle dorsiflexion ROM at the end of the training session, as the last minutes of the training session were the period of time in which there was a high injury risk for the athletes.

2. Materials and Methods

2.1. Design

A cross-sectional observational study was performed in November 2019 following the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) recommendations.

2.2. Participants

A total sample of 38 healthy male individuals aged between 15 and 17 years was recruited from two elite sports and divided into two groups following their sports discipline: A group composed of elite soccer players (n = 18) and B group composed of elite basketball players (n = 20). All the players were taped in both ankle joints, usually for training and competitions with a prescription of the medical doctors from their clubs. Elite U18 individuals followed a training schedule of 3 hours-per-day, 5 days-per-week and played 1 to 2 matches in a week [17]. In addition, both groups were composed of individuals who have played at least 1 time with the national team [18]. Subjects were excluded if: they underwent a physical therapy treatment, suffered any musculoskeletal injury the last 6 weeks, had skins allergy and any history of lower limb surgery, did not complete all the training sessions, and had other foot orthoses.

2.3. Ethical Considerations

The Research and Ethics Committee from the Universidad Europea de Madrid has been approved this research (Villaviciosa de Odón, Madrid, Spain. Record code: 10-04-2019. CIPI/19/157). Before participating in the study, the players and parents were fully informed about the protocol and written informed consent was obtained by the parents of the players. The Declaration of Helsinki was fully respected throughout the study.

2.4. Taping: Procedure and Materials

Ankle taping was performed by two physiotherapists—one for the soccer team and one for the basketball team—both with more than 5 years of experience in taping methods in accordance with Williams et al. [19] procedures and the Sports Medicine Australia [20] guidelines protocol. Before the taping, all of the ankles were covered with a pre-wrap (Rehabmedic, Barcelona, Spain) by the physiotherapist in order to prevent skin alterations for daily use [21]. For the ankle taping, two anchor strips were applied around the leg 10 cm above the malleoli with a 38-mm self-adhesive tape (Leukotape, BSN Medical, Stockholm, Sweden). Secondly, with the foot maintained in a neutral position, two strips were placed from the medial side of the anchor tape and fixing to the lateral side. [19] The “figure sixes” for the subtalar joint were initially placed onto the medial anchor through the plantar surface of the foot to attach back onto the medial anchor. Finally, all the free endings and spaces without tape were covered to complete the ankle taping [19].

2.5. Training Sessions

The training session, in which subjects were evaluated in both groups, consisted of a 90-min technical session and was structured in 3 phases: warm-up (15-min), tactical skills (15-min), and scrimmage (60-min). This session did not comprise of a pre-game or post-game session.

2.6. Outcome Measurements

Ankle ROM assessment was developed by the *Dorsiflex* app (v.2.0, Balsalobre-Fernández, 2017, Madrid, Spain) installed on an iPhone 8 (iOS 12.1, Apple Inc., Cupertino, CA, USA). To measure dorsiflexion ROM, the iPhone 8 was placed at the tibial tuberosity to assess the angle between the tibia and the ground in a weight-bearing lunge position. This procedure was repeated with both legs, and the *Dorsiflex* app reported the dorsiflexion angle for each leg and the percent of asymmetry between the legs. In addition, the *Dorsiflex* app was considered as a valid, reliable, rapid, and easy-to-use tool to assess the ankle ROM and asymmetries in a weight-bearing lunge position [22]. Measurements were made in 3 time periods: (1) baseline, before the practice without bandage; (2) pre-training, immediately after the baseline measurement and before the training session; post-training, immediately after the end of the training session.

2.7. Statistical Analysis

SPSS v.23.0 for macOS (IBM SPSS Statistics for macOS, NY: IBM Corp) was used for statistical analysis. The Shapiro-Wilk test was used to check the normality data distribution. For each group separately, one-way analysis of variance (ANOVA) and Bonferroni’s correction were developed to assess significant differences between the three-time points (basal, pre-training and post-training) and check the multiple comparisons, respectively. The effect size was calculated with the Eta^2 coefficient.

In order to observe the difference between groups, the Student's *t*-test—parametric data—and *U* Mann-Whitney test—no parametric data—were applied to test sociodemographic data between groups. To assess the effects of intra-subjects (time) and inter-subject (treatment groups) values on the dependent variables, a two-way ANOVA for repeated measures was performed (considering the significance of the Greenhouse–Geisser correction when the Mauchly test rejected the sphericity). The Bonferroni post-hoc test was employed for multiple comparisons. Furthermore, the effect size was calculated by the Eta^2 coefficient. The level of significance was set at $p < 0.05$ with an α error of 0.05 (95% confidence interval) and the desired power of 80% (β error of 0.2).

3. Results

Regarding Table 1, the height and weight showed significant differences ($p < 0.05$) between groups. For the soccer group, significant differences were observed for the right ankle [F (2,32) = 7.558; $p = 0.002$ (0.321)] and left ankle [F (2,32) = 9.813; $p = 0.001$ (0.380)], but no differences for the asymmetry variable. The basketball group reported significant differences for the right ankle [F (2,36) = 17.687; $p = 0.001$ (0.496)], the left ankle [F (2,36) = 35.204; $p = 0.001$ (0.662)] and the symmetry [F (2, 36); $p = 0.001$ (0.247)]. (Table 2) The Bonferroni corrections showed significant differences ($p < 0.05$) in the soccer group's right and left ankle between the baseline and pre-training and between the baseline and post-training moments for the right ankle whereas for the basketball group significant differences ($p < 0.05$) were shown for the right and left ankle between baseline and pre-training and in the right and left ankle between pre-training and post-training (Table 3).

The statistical analysis to assess the comparison of the ankle taping between soccer and basketball players reported significant differences in all variables for the time: right ankle [F (2, 68) = 19.022; $p = 0.001$ (0.359)]; left ankle [F (2, 68) = 34.339; $p = 0.001$ (0.503)] and asymmetry [F (2,68) = 7.842; $p = 0.001$ (0.187)].

In addition, the interaction time x group showed significant differences for the asymmetry [F (2, 68) = 0.415; $p = 0.002$ (0.012)]. (Figures 1–3) The Bonferroni corrections for the interaction between groups reported significant differences ($p < 0.05$) for the right ankle, the left ankle and the asymmetry variables between baseline and pre-training moments and the left ankle as well as the asymmetry between pre-training and post-training moments (Table 4).

Table 1. Sociodemographic data of the sample.

Data	Soccer Group (n = 17)	Basketball Group (n = 19)	Total Sample (n = 38)	*p* Value
Age, years	16.00 ± 1.0 †	15.00 ± 1.00 †	16.00 ± 2.00 †	0.005 ††
Height, m	1.73 ± 0.1 *	1.92 ± 0.12 †	1.83 ± 0.12 *	0.001 ††
Weight, kg	68.45 ± 6.75 *	82.04 ± 11.06 *	75.62 ± 11.45 *	0.001 **
BMI (kg/m^2)	22.61 ± 1.63 *	21.93 ± 2.53 †	22.29 ± 1.83 †	0.332 ††

Abbreviations: BMI, body mass index. * Mean ± standard deviation (SD) was applied. ** The Student T-test was performed for independent samples. † Median ± interquartile range (IR) was used. †† The Mann-Whitney U-test was performed.

Table 2. One-way ANOVA for the ankle ROM and asymmetry variables.

Group	Baseline	Pre-Training	Post-Training	Time F (Df); *p* (Eta^2)
Soccer				
Right ankle	39.71 ± 5.33	36.00 ± 6.55	36.88 ± 5.32	F (2,32) = 7.558; *p* = 0.002 (0.321)
Left ankle	38.82 ± 4.87	34.58 ± 5.86	37.49 ± 5.10	F (2,32) = 9.813; *p* = 0.001 (0.380)
Asymmetry	6.44 ± 3.44	10.40 ± 6.90	6.25 ± 5.68	F (2,32) = 3.213; *p* = 0.057 (0.167)
Basketball				
Right ankle	41.00 ± 6.6	37.67 ± 6.4	40.58 ± 5.6	F (2,36) = 17.687; *p* = 0.001 (0.496)
Left ankle	39.56 ± 6.7	34.9 ± 5.3	38.70 ± 5.7	F (2,36) = 35.204; *p* = 0.001 (0.662)
Asymmetry	4.56 ± 3.9	8.7 ± 5.1	5.95 ± 4.5	F (2,36) = 5.913; *p* = 0.001 (0.247)

Abbreviations: ANOVA, analysis of variance; ROM, range of motion. Values are mean ± SD unless otherwise indicated.

Table 3. Bonferroni correction values for the intra-subject (time) effects.

Measure	Right Ankle *p* Value	Left Ankle *p* Value	Asymmetry *p* Value
Soccer			
Baseline			
Pre-training	0.007	0.001	0.116
Post-training	0.021	0.611	1.000
Pre-training			
Post-training	1.000	0.054	0.184
Basketball			
Baseline			
Pre-training	0.001	0.001	0.007
Post-training	1.000	0.575	0.361
Pre-training			
Post-training	0.001	0.001	0.286

Table 4. Two-way ANOVA and Bonferroni correction values for the intra-subject effects of the total sample.

Two-Way ANOVA Values			
	Time F (Df): *p* (Eta^2)		**Time x Group F (Df); *p* (Eta^2)**
Right ankle	F (2,68) = 19.022; *p* = 0.001 (0.359)		F (2,68) = 2.585; *p* = 0.083 (0.071)
Left ankle	F (2,68) = 34.393; *p* = 0.001 (0.503)		F (2,68) = 0.316; *p* = 0.730 (0.009)
Asymmetry	F (2,68) = 7.842; *p* = 0.001 (0.187)		F (2,68) = 0.415; *p* = 0.002 (0.012)
Bonferroni correction values			
Measure	**Right ankle *p* value**	**Left ankle *p* value**	**Asymmetry *p* value**
Baseline			
Pre-training	0.001	0.001	0.001
Post-training	0.009	0.206	1.000
Pre-training			
Post-training	0.009	0.001	0.032

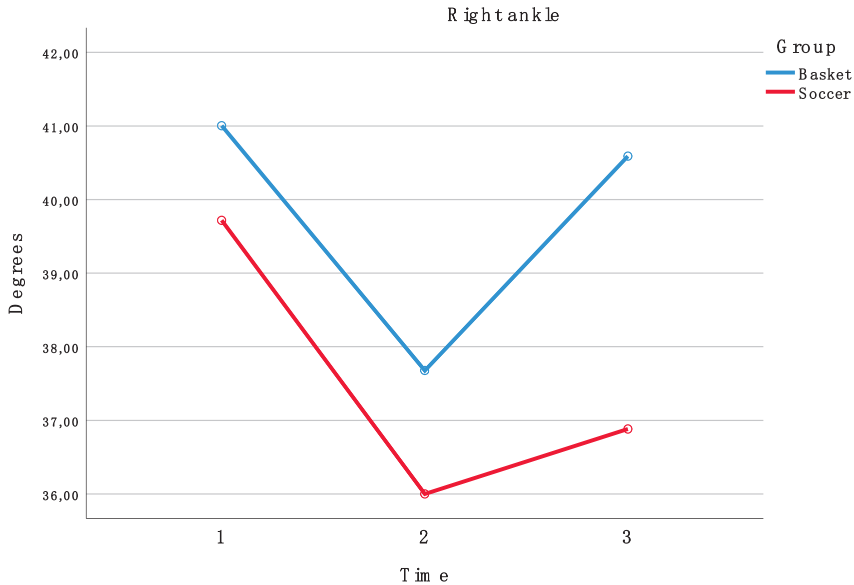

Figure 1. Right ankle ROM values for each group in three measurement times.

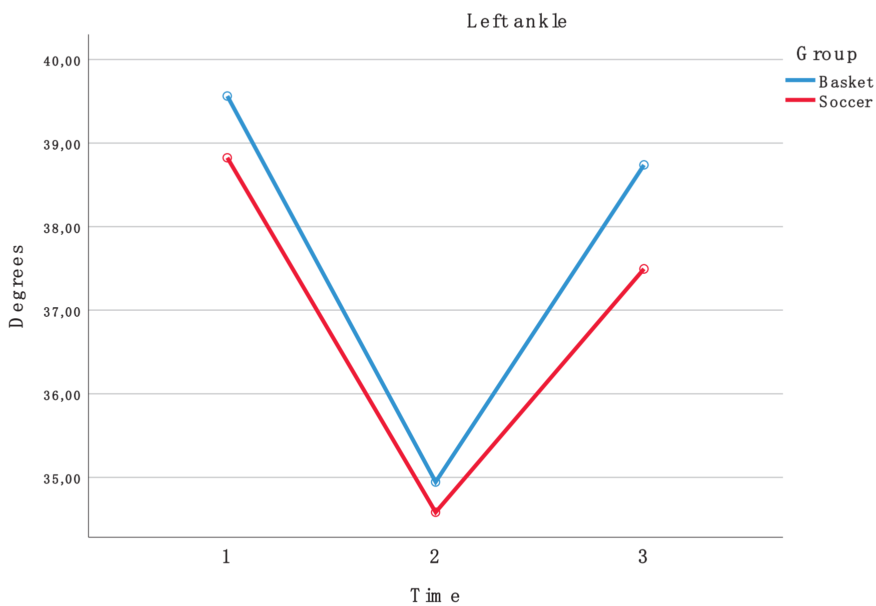

Figure 2. Left ankle ROM values for each group in three measurement times.

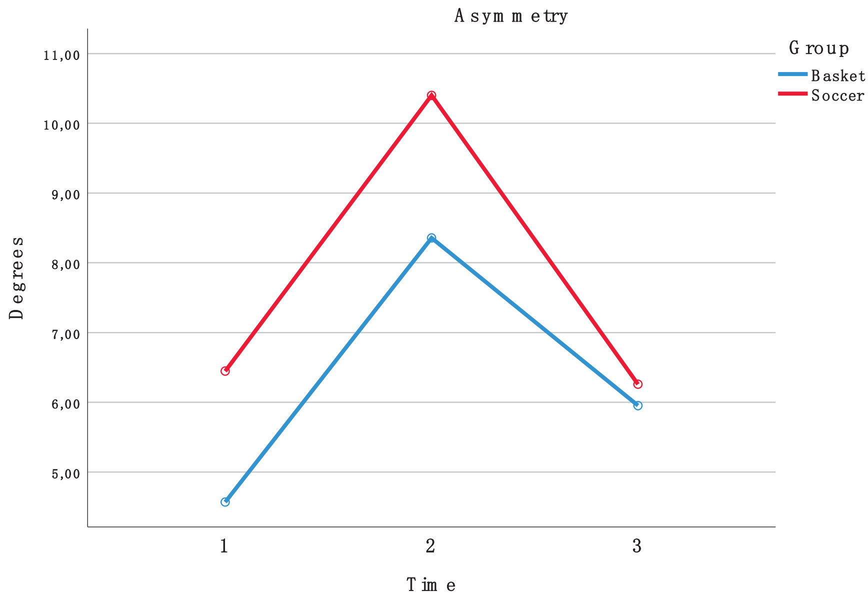

Figure 3. Asymmetry values for each group in three measurement times.

4. Discussion

This research compared the ankle taping on ankle mobility during three specific moments on a daily basis in youth elite soccer and basketball players. The results of the present study suggest that a prophylactic approach, such as ankle taping, is effective for the ROM restriction of the ankle joint immediately after the taping application in soccer and basketball players without differences between groups. However, in the final minutes of the session, where the intensity and the fatigue levels were at its highest peak [23], the ROM values were similar to the baseline values.

According to the findings of the present study, several authors reported the effectiveness of the ankle taping for the ankle ROM restriction [10,12]. For example, Quackenbush et al. argued that the ankle taping was an effective prophylactic method without decreasing jump performance in athletes. [24] Willeford et al. performed a study in collegiate football players and reported that with a bandage of the ankle joint —self-adherent and lace-up ankle brace —a ROM restriction was produced without affecting the dynamic balance [25]. According to the results of the present study, an ankle dorsiflexion ROM increase was observed immediately post-match in soccer players and basketball players—without a bandage [26,27]. However, in both groups, a decrease of ankle dorsiflexion ROM was observed 48 h post-match. Therefore, prevention and recovery strategies in order to minimize the ankle dorsiflexion restriction should be performed in soccer and basketball players. Regarding muscle fatigue and biomechanics, chronic ankle instability and fatigue were related to postural control by disturbances detected on sagittal-plane joints adjacent to the ankle, which may have influence in the ankle dorsiflexion ROM values after training sessions [28].

In addition to the above, landing mechanisms have been defined as a risk factor for ankle sprains in sports populations, De Ridder et al. argued that taping is able to stabilize the ankle joint prior to touch down, placing the ankle joint in a safe position before the landing phase [29]. In addition, Chinn et al. reported that the changes in the foot positioning in individuals with ankle taping could be a protective effect for the prevention of the lateral ankle sprains [30]. In addition, ankle taping increases the confident sense in dynamic-balance activities [31].

Regarding the ankle dorsiflexion asymmetry concept, Rabin et al. determined that weight-bearing ankle ROM should not be assumed to be bilaterally symmetrical [32]. However, the results of the present study reported an asymmetry increase when the taping was applied. Currently, research about the normative values for weight-bearing ankle ROM symmetries reported a dorsiflexion ROM increase of 23% in male military subjects for the dominant side with respect no-dominant side [32]. In the context of the ankle dorsiflexion asymmetry in professional soccer players, Moreno-Pérez et al. reported that ankle dorsiflexion ROM increased after a match in the dominant ankle but decreased 48 h post-match when the post-match assessments in both ankles—dominant and non-dominant—were compared [26]. In this line, a recent study reported that the ankle dorsiflexion ROM was increased post-match from pre-match in both dominant and non-dominant limbs and decreased 48 h post-game in semi-professional players [27]. An asymmetry increase immediately after the ankle tape application could be explained by the restriction of the musculoskeletal structures which surround the ankle joint or alterations of the sensitive proprioception mechanisms due to the taping application [33].

Other useful taping alternatives for ankle sprain prevention could be the kinesiology tape, [7] kinesiotape, [34], or distal fibular taping [35].

4.1. Clinical Considerations

Based on the prior literature and the findings of the present study, it could be supported that ankle taping was an effective and prophylactic method to reduce the ankle dorsiflexion ROM and, consequently, for the prevention of ankle sprain in sports populations. However, the fact that no differences were observed for the soccer left ankle, both basketball ankles from baseline to post-training values could be defined as the ankle taping having “dynamic effectiveness”. Therefore, further research is needed in order to develop new strategies to maintain the initial effectiveness throughout the training session and games. For example, the addition of active stripes or to intensify the ankle taping in the training pauses and games half-times.

4.2. Limitations and Future Lines

Some limitations should be acknowledged in the present study. Although the physical therapist had more than 5 years of experience in taping strategies and functional assessments, the fact that both teams had not been taped and assessed by the same therapist may be a limitation as a human bias for the ankle dorsiflexion ROM and asymmetry were variables. Another limitation could be the fact that just one session was evaluated for each group. Weight, height, and BMI variables were descriptive variables and were found obvious differences between groups. It would be interesting to take them into account for the comparison between groups. In addition, the differences between these two sports in training skills in the footwork and training sessions specific exercises could also be a limitation.

Further research is needed in order to evaluate dynamic balance, landing situations, and lower limb stability with a pressure platform. In addition, electromyography or ultrasound imaging assessments for the muscular activation and the muscle architecture of the muscles related to the ankle joint could be useful to explore the effects of the ankle taping in a deep manner. Several authors reported the effectiveness of ankle taping also in psychological aspects such as better perceptions of confidence and reassurance; thus, it would be interesting to study these variables in soccer and basketball populations.

5. Conclusions

Ankle taping decreased the ankle dorsiflexion ROM in youth elite soccer and basketball players U18. These results could be useful as a prophylactic approach for ankle sprain injury prevention. However, the ankle ROM restriction between individuals without taping, and individuals immediately assessed when the tape was removed after the training was very low. Thus, further research is needed in order to develop new strategies to maintain the initial effectiveness throughout the training session and games.

Author Contributions: Conceptualization, B.D.-L.-C.-T. and C.R.-M.; data curation, D.R.-S., C.L.-N. and C.F.-N.; methodology, P.P.-L., D.R.-S. and D.L.-L.; formal analysis, C.R.-M., D.L.-L. and C.C.-L.; investigation, P.P.-L., C.L.-N. and C.F.-N.; supervision, C.R.-M. and B.D.-L.-C.-T.; writing—original draft preparation, B.D.-L.-C.-T., C.R.-M., D.R.-S. and C.C.-L.; writing—review and editing, B.D.-L.-C.-T., C.R.-M., D.L.-L. and C.C.-L. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The authors thank all of the dancers, doctors and physiotherapists that participated in this project and acknowledge their valuable and essential contribution to the study.

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9

Effect of Football Shoe Collar Type on Ankle Biomechanics and Dynamic Stability during Anterior and Lateral Single-Leg Jump Landings

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Abstract: In this study, we investigated the effects of football shoes with different collar heights on ankle biomechanics and dynamic postural stability. Fifteen healthy college football players performed anterior and lateral single-leg jump landings when wearing high collar, elastic collar, or low collar football shoes. The kinematics of lower limbs and ground reaction forces were collected by simultaneously using a stereo-photogrammetric system with markers (Vicon) and a force plate (Kistler). During the anterior single-leg jump landing, a high collar shoe resulted in a significantly smaller ankle dorsiflexion range of motion (ROM), compared to both elastic (p = 0.031, dz = 0.511) and low collar (p = 0.043, dz = 0.446) types, while also presenting lower total ankle sagittal ROM, compared to the low collar type (p = 0.023, dz = 0.756). Ankle joint stiffness was significantly greater for the high collar, compared to the elastic collar (p = 0.003, dz = 0.629) and low collar (p = 0.030, dz = 1.040). Medial-lateral stability was significantly improved with the high collar, compared to the low collar (p = 0.001, dz = 1.232). During the lateral single-leg jump landing, ankle inversion ROM (p = 0.028, dz = 0.615) and total ankle frontal ROM (p = 0.019, dz = 0.873) were significantly smaller for the high collar, compared to the elastic collar. The high collar also resulted in a significantly smaller total ankle sagittal ROM, compared to the low collar (p = 0.001, dz = 0.634). Therefore, the high collar shoe should be effective in decreasing the amount of ROM and increasing the dynamic stability, leading to high ankle joint stiffness due to differences in design and material characteristics of the collar types.

Keywords: collar height; kinematics; kinetics; dynamic stability; ankle injury

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1. Introduction

Football is the most popular sport in the world, has the largest number of participants, and is associated with a high risk of injury at the professional, amateur, and youth levels during practices and matches [1–5]. It is estimated that somewhere between 13 and 35 players get injured every 1000 competitive hours. The most common incidence of injuries occurs in the lower limbs, mostly ankle sprains [1,5,6]. Dvorak et al. studied injury incidences in the 2010 International Federation of Association Football World Cup. They found that ankle sprains were the most prevalent injury in practices or matches [6]. The impacts of ankle sprains can be severe and include considerable medical expenses, decreased fitness or endurance levels, and missed matches. Furthermore, a common complication of ankle sprains is chronic ankle instability, which results in episodes of the ankle giving way, recurrent sprains, and persistent symptoms such as pain, swelling, limited motion, weakness, and diminished self-reported function. This includes functional and mechanical impairments in isolation, or both [7].

In order to lower football injury risk, shoe manufacturers have attempted to design different cleat configurations that can handle a variety of field conditions, such as turf or grass. In an early study, researchers reported that decreasing the number of cleats and their size may reduce the risk of knee injury [8]. Queen et al. determined that turf cleats could decrease the pressure and force beneath the forefoot, compared to other types of cleats that might minimize metatarsal injury risk on grass [9]. However, Torg et al. examined the mechanical properties of rotational torsion resistance to explain the relation between turf shoes and surface conditions at five temperatures, suggesting that only flat turf football shoes could lower the sprain risk incidence under all conditions [10]. Adjusting cleat configurations could potentially minimize the risk of injuries such as knee sprains and stress fractures on specific field conditions. However, at present, no clear experimental evidence exists to determine the positive effect of cleat configurations on improved ankle stability or decreased ankle sprains.

Increased ankle stability and the prevention of ankle sprains by increasing the shoe collar height have been examined for basketball shoes [11–15]. High collar basketball shoes exhibit a smaller ankle inversion range of motion (ROM), smaller ankle inversion and external rotation at initial contact, and smaller peak inversion velocity, compared to low collar shoes, but no significant difference in kinetic parameters during side-step cutting are observed [11,12]. During jumping tasks, research has revealed that ankle joints show a smaller peak plantarflexion moment and power when wearing basketball shoes with high collars, compared to low collars [13]. According to other research, high collar basketball shoes result in delayed pre-activation timing and decreased amplitude of muscle activity [14]. Therefore, high collar basketball shoes are one factor used to reduce injury potential [16].

Based on the experience with basketball shoes, similar footwear technology has been implemented in football shoes in an attempt to mitigate injury risk. Researchers have observed the ankle inversion between high and low collar football shoes using an inversion platform, which can be rotated 35° to induce a sudden ankle inversion [17]. This research has indicated that high collar shoes significantly reduce the amount and rate of inversion. Additionally, using an arthrometer foot plate, researchers have found that high collar shoes are more effective in decreasing inversion ROM and velocity [18]. However, the research method employed in these previous studies does not accurately portray real-world practices and matches when only the ankle inversion is available. Additionally, although the peak ankle plantarflexion moment and power are significantly smaller in high collar, compared to low collar basketball shoes during landing jumps [13], knowledge of the effects of football shoe collar types on ankle dorsiflexion/plantar flexion movement is currently limited. Furthermore, according to previous studies, around 31% to 46% of football injuries, especially for the knee and ankle, are induced by losing balance or inducing a sprain after landing [19,20]. Hence, for football shoes, questions remain regarding how ankle kinematics and kinetics behave in both dorsiflexion-plantarflexion and inversion-eversion dynamic movements when performing jumping and landing maneuvers.

It should be noted that postural stability has been used to examine the risk of ankle sprain [21,22], and a deficiency in postural stability could play a significant role in increasing ankle sprain risk [20]. A study has found that high collar boots have smaller postural sway, compared to low collar boots, and thereby collar height might have a positive effect on postural control [23]. In a recent study, however, a high collar football shoe did not enhance static postural stability, compared to a low collar shoe [18]. Thus, limited research is available regarding the effects of shoe collars on postural stability. Evidence from a psychological study shows that elastic ankle taping or stiff ankle bracing provides beneficial effects by increasing the feeling of confidence and stability during dynamic-balance tasks [24]. However, direct evidence is conflicting on the beneficial impact on dynamic balance [25–28]. The lack of consistent findings may be due to a lack of measuring more sensitive parameters. The dynamic postural stability index (DPSI) measures three directional components of the ground reaction force during single-leg jump landings. Furthermore, DPSI and its directional components can detect differences in dynamic stability in different football collar types [29]. Therefore, DPSI provides a measure of dynamic stability that has high precision and reliability [30].

Determining the effect of high collar football shoes on ankle biomechanics and DPSI during single-leg jump landings might provide further insight into the biomechanics and dynamic stability of playing football. The purpose of the study aims to determine differences in shoe collar types (i.e., low collar, elastic collar, and high collar) on ankle biomechanics and DPSI during anterior and lateral single-leg jump landings. Our first hypothesis was that smaller ankle ROM, moment, and joint stiffness would result from the high collar football shoe, compared to the elastic or low collar shoes, in both tasks. Our second hypothesis was that dynamic stability would improve when wearing a high collar football shoe, compared to an elastic or low collar shoe, in both tasks.

2. Materials and Methods

2.1. Participants

Fifteen healthy male college football players (age: 21.2 ± 2.0 years; height: 172.4 ± 5.3 cm; body mass: 66.5 ± 9.7 kg) were recruited in this study. The inclusion criteria were (1) at least three years football training experience; (2) foot length of U.S. size 8 for heel-to-toe length; (3) right leg dominant (preferred for kicking); (4) not having sustained a lower limb injury within the past 12 months, including ankle sprain, fractures, or surgeries; and (5) no history of neural or vestibular diseases. The University Ethics Board approved this study, and all participants gave written informed consent before they participated in this study.

2.2. Equipment

Three commercially available football shoes (U.S. size 8, Vapor Untouchable 3; Nike, Portland, OR, USA), which are very popular for football players, were tested in the current study. All shoes were built on the same shoe platform and had identical lightweight upper sections, carbon fiber, thermoplastic polyurethane plates, and cleats, but different shoe collar types: high collar (mass: 300 g; collar height: 70 mm; material: high intensity knitted fabric), elastic collar (mass: 310 g; collar height: 35 mm; material: low intensity knitted fabric), and low collar (mass: 300 g; collar height: 0 mm, material: nil) (Figure 1).

Figure 1. Football shoes used in the current study. (**a**) high collar shoe, (**b**) elastic collar shoe, (**c**) low collar shoe.

The testing environment was an indoor artificial turf-top football ground. The three-dimensional kinematics were measured using a ten-camera Vicon Vantage motion capture system (Vantage 8; Vicon, Oxford, UK), which was arranged around the artificial turf football ground, at a sampling rate of 200 Hz. These cameras are widely used to capture motion trajectory in sports science and biomechanics to optimize human movement [31,32]. The ground reaction force, which was measured for the dominant lower limb, was collected simultaneously using a 600 × 900 mm force plate (9287C; Kistler, Winterthur, Switzerland), which was recessed in the middle of the artificial turf football ground, at a sampling rate of 1000 Hz. The force plate was also used to record the forces exerted by the foot when standing, walking, or running [31,32]. A 900 × 600 × 10 mm artificial turf cover was fixed on the surface of the force plate through screws at each corner (Figure 2). The kinematics and kinetic data were collected and synchronized using a Nexus Lock (Lock +; Vicon, Oxford, UK) with Nexus software (Nexus 2.6.1; Oxford, UK). The Nexus Lock is Vicon's control box for connecting, integrating, and synchronizing third-party devices with the Vicon motion capture system.

Figure 2. Experimental setup.

Thirty-six retroreflective markers (diameter: 14 mm) were attached to the lower limbs using bio-adhesive tapes. The reflective markers were placed on both the right and left limbs of the iliac crest; anterior superior iliac spine; posterior superior iliac spine; lateral/medial prominence of the lateral femora epicondyle; proximal tip of the head of the fibula; anterior border of the tibial tuberosity; lateral/medial prominence of the lateral malleolus; dorsal margin of the first, second, and fifth metatarsal head; and four four-marker rigid clusters were attached bilaterally onto the thigh and shank.

2.3. Protocol

Each participant performed two tasks, anterior and lateral single-leg jump landings, in one day. Therefore, participants were asked to implement either the anterior single-leg jump landing or the lateral single-leg jump landing, while wearing either low, elastic, or high collar football shoes. All of the tasks were first randomized, and then the shoe order was randomized. Prior to data collection, anatomical and tracking reflective markers were placed on the lower limbs, according to the Istituto Ortopedico Rizzoli (IOR) lower limb model [31]. Meanwhile, the shoelaces were tied by an experimenter and the same type of sport socks were worn, in order to avoid the effects of various shoelaces and socks on the results. Participants were provided five practice trials for each task, to become familiar with the reflective markers and tasks. The anterior and lateral single-leg jump landings were normalized by jump distance according to body height, which was 40% and 33% of body height, respectively [33,34]. Additionally, 30 cm and 15 cm hurdles were placed at 10 cm from the edge of the force plate in anterior and lateral single-leg jump landings, respectively. During data collection, participants were positioned at a normalized distance, then they jumped onto the center of the force plate and landed on their dominant leg after receiving the "start" signal from the researcher. For each condition, each participant was required to stabilize as quickly as possible, place their hands on their waist during landing, and remain motionless on the landing leg for 10 s. Trials were discarded and repeated for the following reasons: (1) moving the foot before jumping, (2) touching or collapsing the hurdle during jumping, or (3) losing balance or removing hands from the waist during landing. To prevent fatigue, 2 min and 5 min breaks were provided between trials and tasks. Trials of each condition were collected for three successful jump landings tasks.

2.4. Data Analysis

Visual3D software (C-motion, Inc.; Germantown, MD, USA) was used to analyze the marker positions and force plate data, which were filtered with a low-pass Butterworth filter with cut-off frequencies of 14 Hz and 50 Hz, respectively. The ankle joint angle was defined using the segment coordinate system for the virtual foot segment, which set the ankle joint angle to zero degrees in the static standing, to be aligned with the segment coordinate system for the shank. The ankle joint moment was calculated using Newton–Euler inverse dynamics with the proximal segment of the shank as the reference segment, which was normalized to each participant's body mass. Ankle joint stiffness was calculated as the change in ankle joint moment divided by the change in ankle joint angle from initial contact to peak dorsiflexion [35].

The DPSI is the composite of the vertical (VSI), anteroposterior (APSI), and medial-lateral (MLSI) components, and was computed following the method of Wikstrom et al. [30] using the customized Visual3D software. The square root of the mean square deviation of force, which was the fluctuation from the baseline along each axis of the force plate, was calculated. The APSI and MLSI were assessed using the fluctuations from 0, and the VSI was calculated using the fluctuation from the subject's body weight. The square root of the sum of the squares of APSI, MLSI, and VSI constituted total DPSI.

These variables were calculated using the first 3 s following initial contact, identified as the force threshold exceeding 10 N. The time interval of 3 s is recommended by Wikstrom et al. for studies of sports performance [36]. For anterior single-leg jump landings, the variables of interest included: (1) ankle dorsiflexion ROM, which refers to the total ankle dorsiflexion excursion; (2) ankle eversion ROM, which refers to the total ankle eversion excursion; (3) total ankle ROM in the sagittal and frontal planes, which refers to the total angle changes in the ankle joint in both planes; (4) peak ankle plantarflexion moment, which refers to the maximum plantarflexion moment; (5) peak ankle inversion moment, which refers to the maximum inversion moment; (6) ankle joint stiffness; and (7) APSI, MLSI, VSI, and DPSI, which refer to the assessments of dynamic postural stability. For lateral single-leg jump landings, the variables of interest were similar to the anterior single-leg jump landing, but with two extra variables: (1) ankle inversion ROM, which is the total ankle inversion excursion; and (2) peak eversion moment, which is the maximum eversion moment. The variables of interest are listed in Tables 1 and 2.

Table 1. Mean (standard deviation) of biomechanical variables and pairwise post hoc *p*-value (Cohen's dz) in ankle joint during tasks in the high-, elastic-, and low collar shoe conditions.

Variables	Shoe Collar Condition			Pairwise Post Hoc		
	High	Elastic	Low	H vs. E	H vs. L	E vs. L
Anterior single-leg jump landing						
Dorsiflexion ROM (°) *	10.40 (5.19)	12.83 (4.28)	12.50 (4.16)	0.031 (0.511)	0.043 (0.446)	0.718 (0.078)
Eversion ROM (°)	10.47 (3.48)	11.72 (3.43)	10.09 (2.76)	0.286 (0.362)	0.691 (0.121)	0.030 (0.524)
Peak plantarflexion moment (Nm/kg)	2.38 (0.38)	2.21 (0.36)	2.24 (0.35)	0.095 (0.459)	0.789 (0.383)	1.000 (0.084)
Peak inversion moment (Nm/kg)	0.48 (0.24)	0.58 (0.43)	0.51 (0.31)	0.442 (0.287)	0.696 (0.108)	0.437 (0.187)
Lateral single-leg jump landing						
Dorsiflexion ROM (°)	18.11 (5.13)	20.50 (3.50)	20.62 (2.39)	0.058 (0.544)	0.059 (0.627)	0.907 (0.040)
Eversion ROM (°)	8.85 (3.13)	11.04 (4.29)	9.20 (4.74)	0.005 (0.583)	0.752 (0.087)	0.116 (0.407)
Inversion ROM (°) *	12.10 (3.15)	15.00 (5.88)	12.97 (4.25)	0.028 (0.615)	0.323 (0.233)	0.054 (0.396)
Peak plantarflexion moment (Nm/kg)	2.42 (0.36)	2.39 (0.49)	2.51 (0.48)	1.000 (0.070)	1.000 (0.212)	0.785 (0.247)
Peak inversion moment (Nm/kg)	0.29 (0.21)	0.37 (0.32)	0.31 (0.21)	0.402 (0.296)	0.704 (0.095)	0.496 (0.222)
Peak eversion moment (Nm/kg)	0.35 (0.30)	0.41 (0.26)	0.38 (0.26)	0.471 (0.214)	0.689 (0.107)	0.743 (0.115)

Note. * represents a significant difference within a subject factor. High (H), Elastic (E), and Low (L) represent three football shoe conditions: high collar, elastic collar, and low collar, respectively.

Table 2. Mean (standard deviation) of dynamic postural stability index and pairwise post hoc *p*-value (Cohen's dz) during tasks in the high-, elastic-, and low collar shoe conditions.

Variables	Shoe Collar Condition			Pairwise Post Hoc		
	High	Elastic	Low	H vs. E	H vs. L	E vs. L
Anterior single-leg jump landing						
APSI	0.17 (0.014)	0.17 (0.022)	0.17 (0.024)	1.000 (0.101)	1.000 (0.131)	0.714 (0.194)
MLSI *	0.039 (0.004)	0.040 (0.007)	0.045 (0.006)	1.000 (0.204)	0.001 (1.232)	0.051 (0.116)
VSI	0.42 (0.049)	0.42 (0.050)	0.43 (0.059)	1.000 (0.035)	0.387 (0.234)	0.312 (0.263)
DPSI	0.45 (0.045)	0.45 (0.050)	0.46 (0.058)	1.000 (0.016)	0.569 (0.220)	0.526 (0.225)
Lateral single-leg jump landing						
APSI	0.064 (0.007)	0.063 (0.007)	0.063 (0.010)	1.000 (0.116)	1.000 (0.087)	1.000 (0.007)
MLSI *	0.14 (0.009)	0.14 (0.009)	0.14 (0.012)	0.982 (0.203)	0.359 (0.411)	0.060 (0.588)
VSI	0.39 (0.038)	0.38 (0.049)	0.38 (0.048)	1.000 (0.078)	1.000 (0.159)	1.000 (0.071)
DPSI	0.42 (0.038)	0.41 (0.047)	0.40 (0.060)	1.000 (0.058)	0.547 (0.340)	0.614 (0.270)

Note. * represents a significant difference within a subject factor. High (H), Elastic (E), and Low (L) represent three football shoe conditions: high collar, elastic collar, and low collar, respectively.

2.5. Statistical Analyses

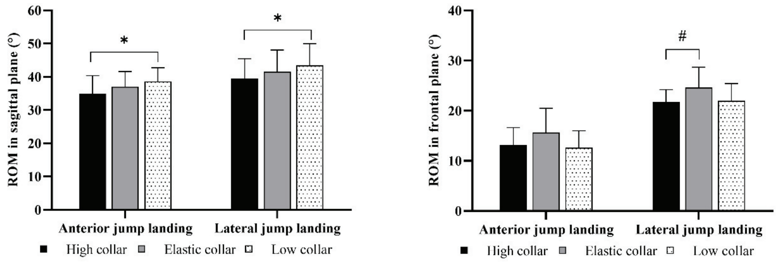
The residual of each dependent variable was assessed for normality using a one-sample Kolmogorov–Smirnov test ($\alpha = 0.05$). Differences between shoe conditions were examined using two (for anterior and lateral single-leg jump landings) one-way within-subject analyses of variance (ANOVA). Pairwise post hoc analyses were conducted to assess significant differences in the main effects. Wilks's Λ and effect size (ηp2) were calculated, and Cohen's dz effect sizes were used to interpret the effect of pairwise comparisons. An alpha level of 0.05 was used for statistical analysis. SPSS (19.0, IBM Inc.; Chicago, IL, USA) was used to conduct all statistical analyses.

3. Results

All the variables of interest were normally distributed. Mean (standard deviation) values of each ankle biomechanical variable and the stability index for each collar type, which were estimated intra-subject first and then inter-subject, are shown in Tables 1 and 2, respectively.

3.1. Anterior Single-Leg Jump Landing

The result of the ANOVA indicated a significant shoe effect on dorsiflexion ROM ($F_{2,28} = 3.829$, $p = 0.035$, Wilks's $\Lambda = 0.675$, $\eta p^2 = 0.639$), total ROM in the sagittal plane ($F_{2,28} = 7.554$, $p = 0.006$, Wilks's $\Lambda = 0.590$, $\eta p^2 = 0.854$), ankle joint stiffness ($F_{2,28} = 7.431$, $p = 0.009$, Wilks's $\Lambda = 0.445$, $\eta p^2 = 0.810$), and MLSI ($F_{2,28} = 7.418$, $p = 0.004$, Wilks's $\Lambda = 0.382$, $\eta p^2 = 0.884$). Post hoc pairwise tests indicated that the high collar resulted in a significantly smaller dorsiflexion ROM, compared to the elastic collar ($p = 0.031$, dz = 0.511) and low collar ($p = 0.043$, dz = 0.446) (Table 1), while a significantly smaller total ROM was observed for the high collar, compared to the low collar ($p = 0.023$, dz = 0.756) in the sagittal plane (Figure 3). The ankle joint stiffness was significantly larger for the high collar, compared to the low collar ($p = 0.030$, dz = 1.040) and elastic collar ($p = 0.003$, dz = 0.629) (Figure 4). MLSI was significantly smaller for the shoe with the high collar, compared to the low collar ($p = 0.004$, dz = 1.232) (Table 2). No other main effects of shoe conditions were detected (Tables 1 and 2).



(**a**) (**b**)

Figure 3. Range of motion (ROM) in the sagittal (**a**) and frontal (**b**) planes for both anterior and lateral jump landings in three shoe conditions: high collar, elastic collar, and low collar. * indicates a significant pairwise difference between the high collar and low collar; # indicates a significant pairwise difference between the high collar and elastic collar.

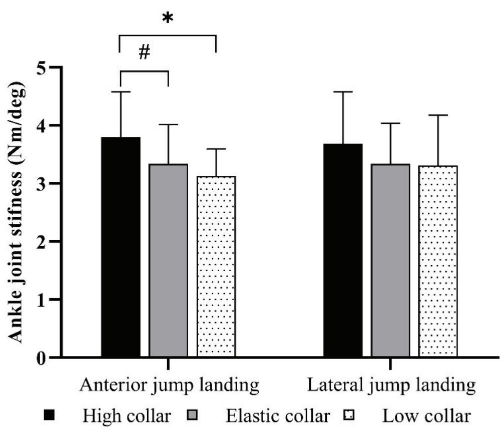


Figure 4. Ankle joint stiffness for both anterior and lateral jump landings in three shoe conditions: high collar, elastic collar, and low collar. * indicates a significant pairwise difference between the high collar and low collar; # indicates a significant pairwise difference between the high collar and elastic collar.

3.2. Lateral Single-Leg Jump Landing

There were significant differences in inversion ROM ($F_{2,28}$ = 4.344, p = 0.029, Wilks's Λ = 0.690, ηp^2 = 0.658), total ROM in both sagittal ($F_{2,28}$ = 6.404, p = 0.009, Wilks's Λ = 0.373, ηp^2 = 0.813) and frontal ($F_{2,28}$ = 6.655, p = 0.006, Wilks's Λ = 0.571, ηp^2 = 0.846) planes, ankle joint stiffness ($F_{2,28}$ = 3.783, p = 0.040, Wilks's Λ = 0.703, ηp^2 = 0.610), and MLSI ($F_{2,28}$ = 7.554, p = 0.041, Wilks's Λ = 0.664, ηp^2 = 0.601) between shoe conditions. Post hoc pairwise tests indicated that inversion ROM was significantly smaller for the high collar, compared to the elastic collar (p = 0.028, dz = 0.615) shoe (Table 1). The high collar resulted in a significantly smaller total ROM, compared to the low collar (p = 0.001, dz = 0.634) in the sagittal plane (Figure 3), while the elastic collar resulted in a significantly larger ROM, compared to the high collar (p = 0.019, dz = 0.873) in the frontal plane (Figure 3). No other pairwise differences were observed for ankle joint stiffness and MLSI (Tables 1 and 2).

4. Discussion

In the present study, we determined the effects of football shoes with different collar conditions on dynamic stability and ankle biomechanical characteristics during anterior and lateral single-leg jump landings. Our results indicate that the high collar football shoe resulted in smaller dorsiflexion ROM and total ROM in the sagittal plane during the anterior single-leg jump landing, while it also decreased inversion ROM and total ROM in the sagittal and frontal planes during the lateral single-leg jump landing. We also found that ankle joint stiffness was significantly larger for the high collar football shoe during anterior and lateral single-leg jump landings, which contradicted our original hypothesis. For dynamic stability, only MLSI showed significant differences during both landing tasks, which was greater when wearing the high collar football shoe and lesser in other conditions; this is partly consistent with our original hypothesis.

The ankle ROM during the anterior single-leg jump landing suggested that the high collar significantly constrained ankle movement, compared to the elastic and low collars. These findings are consistent with Yang et al. and Rowson et al., who reported that peak ankle dorsiflexion or total ankle ROM during a sagittal maneuver was reduced as collar height increases [13,37]. They suggested that collar height and material play an important role in influencing the flexibility and deformation of the whole shoe [13,37]. Additionally, the high collar basketball shoes with strips of plastic that are positioned at the collar's anterior and posterior to the medial and lateral malleoli showed a more restricted ROM of the ankle joint in the sagittal and frontal planes, compared to no plastic condition [16]. It is noteworthy that the elastic collar could not constrain the ankle movement, which might have been due to the low rigidity or high elasticity of the collar material. However, there was no significant change in the frontal plane's ROM. One possible reason is that our healthy participants might have had few inversion-eversion movements during the anterior single-leg jump landings, because our results detected significant differences in inversion and total ankle ROM in the frontal plane between the high and elastic collar, but not between the high and low collar during lateral single-leg jump landings. The elastic collar, similar to ankle taping, likely provides a feeling of confidence and stability [18,24]. This result, in our perspective, is in disagreement with a recent report that indicated that high collar basketball shoes do not restrict the peak inversion angle (29.3° vs. 28.3°) and ROM (17.4° vs. 15.2°) in a self-initiated drop landing on an inversion platform [14]. However, our findings are supported by Richard et al., who found that a high collar football shoe effectively reduces the amount of inversion by 4.5° (38.1° vs. 42.6°) after an inversion platform drop [17]. It is possible that a self-initiated drop landing on an inversion platform does not reach the limitation boundary of the inversion for a high collar basketball shoe. During side-step cutting, Liu et al. and Lam et al. found that the ankle inversion angle, peak inversion velocity, and total inversion ROM are reduced as collar height increases [11,12]. Therefore, there is a restricted angle for an inverted ankle joint position, which might effectively increase ankle joint stability and reduce the risk of ankle sprain injury [11,12]. In our study, the dorsiflexion and total sagittal ROM showed moderate-to-large effect sizes with the high collar, compared to the other collars. Therefore, the football shoe's higher collar height used in this study could constrain ankle dorsiflexion and the inversion angle during both longitude and widthwise tasks, potentially reducing the risk of ankle sprain injury.

Several prior studies have examined the effect of collar conditions on ankle kinetics. Lam et al. detected no difference from collar conditions on the ankle inversion moment during side-step cutting [12]. In addition, Yang et al. reported that high collar basketball shoes could reduce the plantarflexion moment during lay-up jumps, but not drop jumps [13]. The authors suggested that these differential findings were caused by different upper limb positions, movement patterns, and force requirements, as well as the coordination of active and antagonist muscles [13]. These findings are in agreement with our results showing either no significant change or a small effect size in the ankle inversion moment for both tasks; however, different jump maneuvers that are high-frequency and risky during practices or matches still need to be tested. Interestingly, ankle joint stiffness was significantly increased when wearing the high collar football shoe, compared to the other shoes. Theoretically, ankle joint stiffness is calculated using the change in joint moment divided by the change in joint angle [35]. Although the change in ankle moment was not measured in our study, it is possible that the enhanced ankle joint stiffness from the high collar football shoe may be due to a decrease in total ankle

ROM in the sagittal plane. Given the primary role that joint stiffness plays in lower limb injuries [38], overuse injuries at the ankle joint might increase as collar height increases.

Our findings also suggest that MLSI is improved as the height of the football shoe collar increases. A couple of studies have examined the effect of collar height on static or dynamic postural stability [18,39]. However, according to previous research, adequate dorsiflexion ROM is essential for dissipating the ground reaction force [40] and has a positive influence on DPSI [30]; these findings conflict with the results of our study. However, evidence from ankle taping and bracing indicate an increased sense of confidence and stability [24]. Inconsistent findings across studies regarding the dynamic stability of ankle taping or bracing might be due to subjects with or without injury [25–28]. Furthermore, although the current study showed a significant difference in MLSI between shoe conditions during lateral single-leg jump landings, post hoc analysis indicated no pairwise difference, and small effect size. Therefore, this phenomenon still needs to be confirmed, and additional quantitative studies on DPSI are warranted.

There are some limitations to the present study. First, only healthy male college football players were recruited as subjects. Players with functional ankle instability may have different responses to shoe collar conditions, especially for DPSI. Second, it should be noted that our current findings were limited to anterior and lateral single-leg jump landings. Future studies should investigate other typical movements that have high injury risk, such as side-step cutting. Third, different types of shoes may have different mass, which could affect biomechanical responses. A better-controlled experiment is to match the shoe mass across conditions. Fourth, the long-term effect of shoe collar conditions on the incidence of lower limb injuries has yet to be examined. Long-term prospective studies are needed. Finally, the current study only focused on the biomechanical changes at the ankle joint, while knee and hip joint kinematics and kinetics and muscle activity data were not collected.

5. Conclusions

In the current study, the association between the collar condition of football shoes and ankle biomechanics and dynamic postural stability was analyzed. Ankle joint ROM and MLSI during a single-leg jump landing were reduced and improved as the height of the collar increased, respectively. In addition, higher ankle joint stiffness was found for the high collar, compared to the low collar football shoe. Ankle biomechanics and MLSI information from different collar types may be useful in designing football footwear and implementing training. Future prospective investigations are warranted to determine the influence of different shoe collar heights, ankle kinematics/kinetics, and DPSI on lower extremity risks.

Author Contributions: This paper is a result of the collaboration of all authors. All authors have previous experience in sport biomechanics that was shared in order to reach the results discussed in this paper. Conceptualization: Y.T. and Z.W.; data curation: Z.W. and Y.Z.; formal analysis: Y.T. and J.P.; funding acquisition: Y.L.; investigation: Y.Z.; methodology: Y.Z. and S.W.; project administration: Y.L. and J.P.; resources: Y.T. and Y.L.; software: Z.W. and J.P.; supervision: Y.L.; validation: S.Z., S.W., and Y.L.; visualization: Z.W.; writing—original draft: Y.T.; writing—review and editing: S.Z., Y.L., and J.P. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The authors thank all participants for their contributions.

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Change of Direction Performance Is Influenced by Asymmetries in Jumping Ability and Hip and Trunk Strength in Elite Basketball Players

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Abstract: Change of direction (COD) ability is essential for sport performance in high level team sports such as basketball, however, the influence of asymmetries on COD ability is relatively unknown. Forty-three junior and senior level elite basketball players performed isometric hip and trunk strength testing, passive hip and trunk range of motion testing, and unilateral horizontal and vertical jumps, as well as the T-test to measure COD performance. Mean asymmetry values ranged from 0.76% for functional leg length up to 40.35% for rate of torque development during hip flexion. A six-variable regression model explained 48% (R^2 = 0.48; p < 0.001) of variation in COD performance. The model included left hip internal/external rotation strength ratio, and inter-limb asymmetries in hip abduction rate of torque development, hip flexion range of motion, functional leg length, single leg triple jump distance, and peak torque during trunk lateral flexion. Results suggest that the magnitude of asymmetries is dependent of task and parameter, and using universal asymmetry thresholds, such as <10 %, is not optimal. The regression model showed the relationship between asymmetries and COD performance. None of tests were sufficient to explain a complex variable like COD performance.

Keywords: asymmetry; agility; basketball; strength; power; inter-limb asymmetry

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1. Introduction

Inter-limb asymmetry has been mostly researched from the aspect of sports injury risk, especially in view of athletes returning to sport after anterior cruciate ligament reconstruction [1–4]. Only recently, the relationship between inter-limb asymmetry and sports performance has been a popular topic of investigation [5,6]. Inter-limb asymmetry is found to be a normal adaptation in many sports that involve unilateral movements (e.g., cricket) [7], but further research in team sports is needed to elucidate whether asymmetries influence performance or injury risk [5,6]. Lately researchers are trying to elucidate whether asymmetries (and which particular type of asymmetry) influence performance [8]. Inter-limb asymmetry may present at the level of different motor abilities (e.g., strength, power, and range of motion) and can be measured locally (e.g., one joint) and globally (e.g., within a complex movement, such as vertical jump). Therefore, various methods have been used for its quantification [9], however, many studies used local knee isokinetic dynamometry [10,11], isometric mid-thigh pull (IMTP) [12,13] or vertical jump tests [14–18]. Further, Sheppard and Young´s [19] model of change of direction (COD) determinants showed that asymmetries could negatively affect COD performance. However, supporting evidence is inconsistent.

Two studies investigated the relationship between local inter-limb knee strength asymmetry and performance in COD. Lockie et al. [10] showed mostly positive correlation between different parameters and speed of isokinetic strength asymmetries during knee flexion and extension and T-test performance ($r = 0.638$, 0.669, $p < 0.01$). Exception was one negative correlation ($r = -568$, $p < 0.01$) between peak torque during knee extension (240°/s) and T-test performance. Similarly, Coratella et al. [11] observed that the same local asymmetries negatively impact COD performance (T-test and 180° turn test) ($r = 0.397$–0.614, $p < 0.05$). As the mentioned studies measured local strength asymmetries in the knee joint, they demonstrate the need to study proximal body parts like hip and trunk.

When it comes to the relationship between global asymmetries and performance in COD, results are less consistent. Many studies, using different tests for assessing asymmetries and COD performance, did not detect a relationship between global asymmetries and COD performance. Chiang [12] investigated the relationship between peak torque asymmetry during IMTP and COD ability (assessed as 180° turn test) and reported no significant correlation. However, he used bilateral IMTP to quantify asymmetry, which may have influenced methodological validity. While this methodological shortcoming was corrected by Dos Santos et al. [13], who used unilateral IMTP test, they have not found any significant correlation between inter-limb asymmetry in various parameters related to unilateral IMTP and COD performance ($r \leq 0.35$, $p \geq 0.380$). Hoffman et al. [14] have not found any significant correlation between asymmetry in single-leg countermovement jump (SLCMJ) height and COD ability (three-cone drill). Although reporting high average asymmetry in jump height and length (up to 10.2%), Lockie et al. [15], have not found any significant correlation between these asymmetries and COD (505 and T-test) performance ($r = 0.00$–0.018, $p = 0.31$–0.99). Similarly, Dos Santos et al. [16] found no significant correlations between asymmetries in horizontal jumping tasks and performance in two COD tasks ($r \leq 0.35$, $p > 0.05$). Furthermore, Fort-Vanmeerhaeghe et al. [20] have not found a relationship between asymmetry in jump height during SLCMJ and V-cut COD test ($r = 0.10$, $p > 0.05$). Finally, Loturco et al. [18], have found no significant correlation between asymmetries in different parameters during single leg vertical jumps and performance in zig-zag test.

By contrast, few studies have found a significant correlation between global asymmetry in jumping tests and COD performance. Studying female soccer players, Bishop et al. [21] found a significant positive correlation between inter-limb asymmetry in single-leg depth jump height and performance in 505 COD test on left ($r = 0.66$, $p < 0.01$) and right ($r = 0.52$, $p < 0.05$) side. Another study that reported a relationship between asymmetry and performance was of Maloney et al. [22], that explained 63% ($p < 0.001$) of variance of COD performance with leg stiffness and height asymmetry during vertical depth jump.

The reason for inconsistent findings could lay in discrepancies among populations, methods of asymmetry calculation, and COD tests, as well as in low asymmetry values, that are not large enough to influence performance. Taking that into consideration, Sarabon et al. [23] found that explosive strength parameters like rate of torque development (RTD) are more sensitive to detect inter-limb asymmetries compared to maximal strength outcomes like peak force or peak torque during maximal voluntary contractions (MVC), which were used in previous research. Also, local inter-limb asymmetries were assessed only for the knee joint, while proximal regions of hip and trunk were overlooked. Moreover, asymmetries in range of motion were not previously researched in relation to performance. A substantial portion of asymmetry studies was done on amateur athletes and soccer players, which does not give enough insight into the functioning of elite athletes and other team sports, such as basketball. Basketball is characterized by many high intensity changes of direction (COD) [24], indicating that COD ability plays a critical role in basketball performance.

Therefore, the aim of this study is two-fold: (a) to profile elite basketball players in different local strength and range of motion asymmetries of hip and trunk region, and global power asymmetries in horizontal and vertical jumping and (b) to quantify the relationship of those asymmetries with COD performance. We hypothesized that these asymmetries could predict COD performance.

2. Materials and Methods

2.1. Subjects

Forty-three (17 senior and 26 junior) male elite basketball players (age = 20.54 ± 6 years; height = 194.48 ± 7.19 cm; body mass = 86.77 ± 10.13 kg) from three different professional basketball clubs (Adriatic basketball association league (all three clubs); Liga Nova KBM, Slovenia (one club), and Premier Croatian basketball league (two clubs)) volunteered to participate in the study. A minimum sample size of 18 participants was determined from an a priori power analysis (G*Power 3.1, Heinrich-Heine-Universität, Düsseldorf, Germany) based upon an estimated squared multiple correlation of 0.45 and a power of 0.8 [25]. Subjects were in training program from 18 to 24 h per week, had at least one-year experience in resistance training and reported no previous (within the last 12 months) or present lower-limb injuries. All subjects provided informed consent to participate in the study. For the underage subjects their parents or guardians signed consent prior to their participation. This study was a part of TELASI–PREVENT (Body asymmetries as a risk factor in musculoskeletal injury development: studying etiological mechanisms and designing corrective interventions for primary and tertiary preventive care—L5-1845) project which was approved by Slovenian Medical Ethics committee.

2.2. Procedures

The study was conducted in February of 2019, in the middle of the 2018/2019 basketball season. Testing was performed in each of the clubs playing/training courts. All tests were performed during a single testing session lasting approximately 180 min per participant. Participants attended the sessions in larger groups and rotated between the testing sessions (see below). The subjects were instructed to refrain from any physical activity for at least 24 hours before testing. Testing started with anthropometric measurements, after which the subjects performed a warm-up (5 min of low intensity running, 8 repetitions of dynamic stretching and body weight activation exercises). After the warm-up, subjects were randomized into 4 groups to complete four testing stations in a random order: (i) jumping, (ii) COD, (iii) hip and trunk dynamometry; and (iv) hip and trunk range of motion (ROM). There was a 5-minute rest between the testing stations. Each test began after the subject reported that they felt comfortable with the task (no more than 3 practice trials were taken by a player).

2.2.1. Functional Leg Length

Functional leg length was defined as the distance between anterior-superior iliac spine (ASIS) and the ground, and was measured with laser distance meter (LD 420, Stabila, Hungary). The subjects were instructed to stand with their bare feet on the ground, heels next to the wall, with feet separated hip distance apart. During left leg measurement subjects were instructed to put their left hand on the right shoulder and vice versa. Three measurements on each leg were performed and the mean from these three repetitions was taken for further analysis.

2.2.2. Single-Leg Countermovement Jump

SLCMJ was performed on a force platform (Type 9260AA, Kistler, Winterthur, Switzerland). Subjects were informed to step on the force platform with their testing leg and hands on their hips. The opposite leg was slightly flexed at the knee, but was not touching the shin of the tested leg. Swinging with the opposite leg during jumping was not allowed. The subjects were instructed to jump as high as possible, with the countermovement depth being self-selected, land on two legs and a hold balanced position for 3 s. The jump would be accepted if all of the above-mentioned instructions were met. Three trials on left and right leg were performed with 30 s of rest between each trial. Peak force (N), peak power (W), and highest jump height (m) for each leg was taken for further analysis.

2.2.3. Single-Leg Horizontal Jump

Tape measure was used to measure Single leg horizontal jump (SLHJ), which was performed on the basketball court sufficing the standards of international basketball federation (FIBA). Subjects were informed to put their testing leg with toe at the starting line and hands on the hips. Subjects performed a countermovement to self-selected depth before pushing themselves into the horizontal jump, landing onto both legs and holding a balanced position for 3 s. Three trials on each leg were performed with 30 s of rest between each trial. The distance (m) was measured to the nearest 0.01 m with a tape measure. The longest jump from each leg was taken for further analysis.

2.2.4. Single-Leg Triple Jump

Single leg triple jump (SLTJ) was measured similarly to SLHJ. Subject performed three consecutive horizontal jumps in which they landed onto both legs and held a balanced position for 3 s. The jump would be accepted for if all of the above-mentioned instructions were met. As with the SLHJ, the longest of the three jumps was taken for further analysis for each leg.

2.2.5. Single-Leg Lateral Jump

Tape measure was used to measure Single leg lateral jump (SLLJ). Subjects were informed to put the inner (i.e., medial) edge of their feet at the starting line and hands on their hips. When a subject was ready, he performed a countermovement to self-selected depth before pushing himself into lateral jump landing onto both legs and holding a balanced position for 3 s. Three trials on left and right leg were performed with 30 s of rest between each trial. Distance (m) was measured to the nearest 0.01 m with a tape measure. Longest jump from each leg was taken for further analysis.

2.2.6. Trunk Strength

Trunk strength assessment was done according to Markovic et al. [26] protocol. A trunk dynamometer (S2P Ltd., Ljubljana, Slovenia) with a bending beam load cell (model 1-Z6FC3/200 kg, HBM, Darmstadt, Germany) was used to measure trunk flexion, extension, and lateral flexion isometric strength. Isometric strength was measured as peak torque (Nm/kg) of the best one second interval during maximal voluntary contraction. All of the output variables were normalized with subject's body mass. During trunk extension measurement, subjects were standing with back turned towards the dynamometer with sensors on level of scapular spine and hands crossed on their shoulders. During trunk flexion measurement, subjects were standing turned face towards dynamometer with sensors on the same level as during extension and arms floating in the air to prevent their contribution. During trunk lateral flexion, subjects were standing sideways to the dynamometer, positioned so that their spine was in neutral position. The hand closer to the sensor was placed on their opposite shoulder and the other one was placed on opposite hip. During all trunk strength measurements, subjects were in their training shoes, standing with feet hip width distance apart, while a rigid strap was tightly fastened across pelvic girdle to achieve good fixation. During every trial subject was verbally encouraged to reach his best performance and hold it for 3–5 s. Each task was done three times with 60 s of rest in between. The best result for each task was taken for further analysis.

2.2.7. Hip Strength

Hip strength assessment was modeled based on Markovic et al. [27] protocol. A multipurpose dynamometer (Muscleboard, S2P Ltd., Ljubljana, Slovenija) was used to measure hip flexion, extension, abduction, adduction, internal and external rotation strength. Peak force values were multiplied by lever arm (leg length, in meter) to calculate hip torque. Isometric strength was measured as peak torque (PT) (Nm/kg) during one second interval of maximal voluntary contraction and rate of torque development (RTD) (Nm/ms) was measured in 100 ms interval as Δ torque/Δ time value. During all of the measurements, the offset of the sensor was performed with the relaxed leg, but with the subject having minimal contact with sensor (~5% MVC). Then, the subject was instructed to reach MVC as fast as possible. During all measured actions (except hip rotations), the distance between the mid-part of the aluminum brace of sensor and medial malleoli was set to 5 cm and a rigid strap was tightly fastened across pelvic girdle to achieve good fixation. Hip flexion and extension were measured unilaterally while the remaining tasks were performed bilaterally. During hip flexion (Figure 1A) subject was sitting on dynamometer with hands on the ground and the tested leg extended in knee with hip flexion (~30°), while the non-tested leg was on the ground with knee flexion of ~90°. During hip extension (Figure 1B) subject was laying prone on elbows on the ground, with the tested leg extended, non-tested leg was in the 90° knee flexion, resting on dynamometer surface. During abduction and adduction (Figure 1C) subject was sitting with legs hip apart, knees fully extended and hip in ~30° flexion. During hip internal and external (Figure 1D) rotation, the subject was kneeling on all fours with knees and hip in 90° flexion with knees hip apart. The best out of three results from each movement was taken for further analysis.

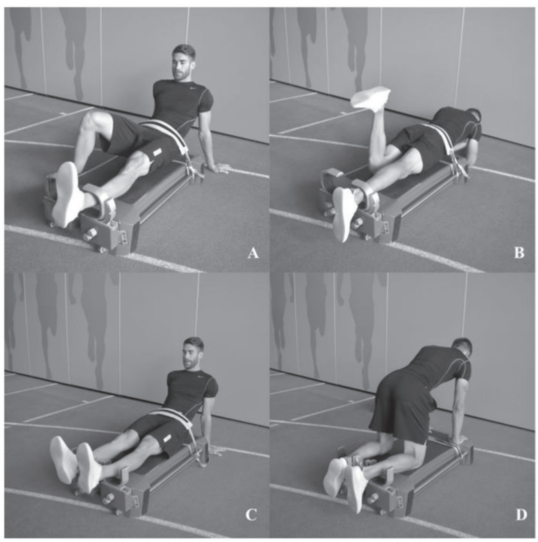

Figure 1. Position of subjects during isometric hip strength testing. (**A**) flexion; (**B**) extension; (**C**) abduction/adduction; and (**D**) internal/external rotation.

2.2.8. Range of Motion

Passive hip range of motion (ROM) during flexion, extension and internal/external rotation was measured with a digital inclinometer (Baseline, Fabrication Enterprises Inc., White Plains, NY, USA) and abduction/adduction with a handheld goniometer (Baseline, Fabrication Enterprises Inc., White Plains, NY, USA). All of the measurements were performed by the same measurer to minimize error. For flexion and extension, the inclinometer was aligned between the tested side femur trochanter major and lateral condyle. Hip flexion ROM was measured with the subject in supine position (the non-tested leg was extended in knee and hip fixated) and the knee of the tested leg in extended position. The tested leg was then moved and kept extended during whole movement until first pelvic movement. During hip extension ROM, subject was in prone position, and tested leg was kept in knee flexion (~90°) during whole movement until first pelvic movement. Hip internal/external rotation ROM was measured with the inclinometer located in the center of vertically positioned (with pendulum) tibia with the subject in pronated position and knee in 90° flexion. Internal and external rotation were performed until the first pelvic movement, with hand-stabilization on the pelvis. Hip abduction and adduction ROM were measured with goniometer with stationary arm pointed toward the opposite anterior superior iliac spine and the movable arm pointed toward the patella of the tested leg. During abduction, the subject was laying supine with both legs in neutral position (start) from which the tested leg was moved into abduction until first pelvic movement (finish). During adduction, the subject was supine with non-tested leg laying from table in ~30° abduction and tested leg in neutral position (start) from which leg was moved into adduction until first pelvic movement (finish). Mean result from three attempts on each leg was taken for further analysis with all of the results expressed in degrees (°).

For the trunk lateral flexion ROM, the subject was standing barefoot with feet hip width distance apart with his back and heels touching the wall. Starting position was measured with a tape as distance between the middle finger (hand on the wall) and the floor. Subjects performed lateral flexion, sliding downwards with the hands without breaking contact with the wall and lifting their heels of the ground. At the end of movement, the end position was measured, and the difference between starting and end position was calculated. Mean result from three attempts on each side was taken for further analysis with all of the results expressed in meters (m).

2.2.9. Change of Direction

For COD performance, the T-test (Figure 2) was used, as outlined by Semenik [28]. All of the COD testing was done on the basketball court sufficing the standards of international basketball federation (FIBA) using photocells timing gates (Brower Timing Systems; Draper, Utah). At the beginning of test, the subject was standing 30 cm behind the start/finish line where photocells were placed. Subject was instructed to sprint (filled line up in Figure 2) from the start to the first cone, touch the tip with one hand, shuffle (dashed lines in Figure 2) to the cone opposite of the touching hand and touch the tip of the lateral cone, then shuffle to the third cone and touch it with the first hand, shuffle back to the middle cone touching the tip with the second hand and then pedal back (filled line down in Figure 2) to the finish line. One-minute recovery was given between each trial. The best out of three trials was taken for further analysis.

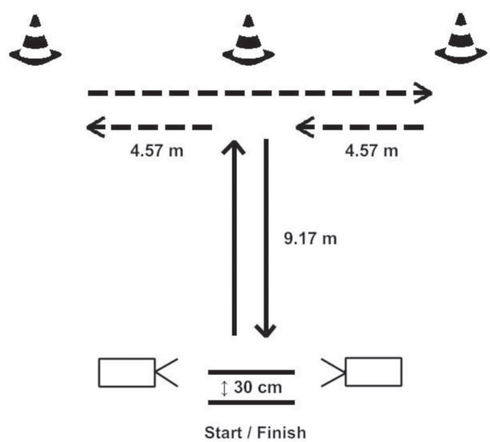

Figure 2. Schematic representation of the T-test.

2.3. Statistical Analyses

Due to the unknown reliability of the strength assessment with a novel MuscleBoard device (S2P Ltd., Ljubljana, Slovenia), particularly in view of RTD, we checked the intra-session reliability of the strength outcome measures that were used as potential predictors for COD performance. We used (a) intra-class coefficient correlation to assess relative reliability, (b) absolute typical error and relative typical error (expressed as coefficient of variation) to assess absolute reliability, and (c) paired-sample two-tailed T-tests to check for systematic bias. We used the data from our larger study involving 115 basketball players, who had completed the exact same protocol for strength assessment, the only difference was the lower number of repetitions (2 compared to 3 in our study) for each task. We used guidelines of Koo and Li [29] for reporting Intraclass Correlation Coefficient (ICC). Based on the 95% confident interval of ICC estimate values < 0.5 = poor, 0.5–0.75 = moderate, 0.75–0.90 = good, and > 0.90 = excellent reliability.

We used multiple regression analysis to model prediction of COD performance (dependent variable) with asymmetries (independent variable). Independent variables were grouped into five categories of asymmetries (anthropometric asymmetries, lateral hip and trunk strength asymmetries, hip and trunk strength ratios, hip and trunk ROM asymmetries and jumping asymmetries)—a total of 33 potential independent variables.

Inter-limb asymmetry was calculated with the following equation [30]:

$$Asymmetry\ (\%) = \left(\frac{stronger - weaker}{stronger}\right) \times 100$$

Shapiro–Wilks tests were performed to assess the normality of distribution of independent variables; only 24 % (8/33) were considered to be normally distributed given an alpha level of $p > 0.05$. Step-wise regression analysis was performed for overall CODS performance using all independent variables. An analysis of standard residuals was carried out, which showed that the data contained no outliers (s standardized residuals minimum: −1.71, standardized residuals maximum: 2.51). A collinearity test indicated that multicollinearity was not a concern (minimum tolerance: 0.75, maximum VIF:1.33). The data met the assumption of independent errors (Durbin–Watson value: 2.26). Also, Breuch–Pagan (10.43, $p > 0.05$) and Koenker (8.32, $p > 0.05$) test indicated the homoscedasticity of the model. Statistical significance was set at alpha level of $p \leq 0.05$ and all statistical procedures were conducted using the Statistical Package for the Social Sciences for Windows (v.26.0; SPSS Inc., Chicago, IL, USA). Mann–Whitney U test was used to for testing statistical significance in difference between hip PT and RTD, and left and right leg strength ratios.

3. Results

The results regarding reliability analyses are summarized in Table 1. No systematic bias was present for any of the outcome measures. Relative reliability was good to excellent for the peak torque measures (ICC > 0.80) and acceptable for RTD measures (ICC = 0.5–0.8). Typical errors, expressed as coefficient of variation were low for peak torque measurements for adduction, abduction, and internal rotation, but higher (>10%) for external rotation, flexion, and extension, and for all RTD outcomes. This suggests that the predictive strength of the parameters related to hip strength in this study can be used on the level of a sample with high confidence, while the generalizability to an individual must be done with high caution.

Inter-limb asymmetry values ranged from 0.76% for functional leg length up to 40.35% for RTD during hip flexion (Table 2). Inter-limb asymmetries of hip peak torque were lower (except for internal rotation) than the rate of torque development (3.68–11.52% vs. 10.72–40.35%, $p < 0.05$) (Table 3). Hip extension/flexion (1.32 ± 0.33; 1.30 ± 0.25), abduction/adduction (1.08 ± 0.19; 1.07 ± 0.20) and internal/external rotation (1.13 ± 0.27; 1.18 ± 0.26) ratios were similar ($p > 0.05$) for the left and right side (Table 4). Mean inter-limb asymmetry in peak torque during trunk lateral flexion exceeded the 10% threshold (12.48 ± 9.61 %). Mean inter-limb asymmetry in hip ROM (5.91–13.54%), was above the 10% threshold for extension and internal/external rotations, while the trunk lateral flexion showed good symmetry (2.01 ± 1.27%). Asymmetries in horizontal jumps showed lower results (3.48–4.60%) than various parameters of SLCMJ (4.77–11.12%).

Table 1. Reliability results for outcome measures.

Outcome/Task		Repetition 1		Repetition 2		Systematic Bias		Relative Reliability			Absolute Reliability			
		Mean	SD	Mean	SD	T	P	ICC	95% CI for ICC		TE	CV	95% CI for CV	
Peak torques at the hip (Nm)	Hip Abduction—Left	73.1	18.8	72.9	19.8	0.908	0.365	0.97	0.96	0.98	3.4	4.65	4.59	4.74
	Hip Abduction—Right	71.9	18.6	71.5	19.4	1.384	0.168	0.97	0.96	0.98	3.3	4.54	4.49	4.63
	Hip Adduction—Left	70.4	19.5	71.2	19.7	−1.695	0.092	0.93	0.91	0.95	5.0	7.09	6.90	7.43
	Hip Adduction—Right	69.0	19.1	69.8	19.3	−1.435	0.153	0.93	0.91	0.95	5.0	7.16	6.96	7.50
	Hip Internal rotation—Left	73.1	21.7	72.6	20.7	0.617	0.538	0.92	0.89	0.94	5.9	8.06	7.82	8.51
	Hip Internal rotation—Right	74.8	20.9	74.6	19.9	−0.592	0.555	0.93	0.90	0.95	5.4	7.26	7.06	7.63
	Hip External rotation—Left	62.5	32.2	64.5	16.8	0.172	0.872	0.85	0.80	0.88	10.2	16.06	15.07	17.69
	Hip External rotation—Right	63.8	16.6	63.7	16.3	−0.263	0.793	0.86	0.81	0.90	11.5	17.99	17.01	19.83
	Hip Flexion—Left	139.8	45.9	138.8	39.8	−0.554	0.712	0.94	0.91	0.96	20.6	14.77	14.33	15.53
	Hip Flexion—Right	146.1	42.7	146.8	42.7	−0.114	0.909	0.96	0.94	0.97	18.2	12.41	12.19	12.79
	Hip Extension—Left	163.3	71.5	160.9	55.2	1.195	0.234	0.84	0.78	0.88	27.8	17.13	15.99	19.30
	Hip Extension—Right	169.4	53.0	169.4	50.6	−0.721	0.472	0.91	0.87	0.93	16.6	9.83	9.45	10.51
Peak force at the trunk (N)	Trunk extension	534.5	199.2	560.3	190.7	−3.506	*0.001*	0.88	0.83	0.91	65.3	11.82	9.64	13.32
	Trunk flexion	415.5	144.2	431.0	144.9	−4.106	*0.000*	0.94	0.91	0.96	33.5	7.91	5.42	9.11
	Trunk lat. flexion—Left	395.4	121.2	393.9	125.3	0.114	0.910	0.88	0.84	0.91	51.8	13.1	10.02	15.89
	Trunk lat. flexion—Right	395.3	129.8	405.5	129.8	−2.474	*0.014*	0.92	0.88	0.94	36.8	9.22	7.88	11.76
Hip RTD (Nm/s)	Hip Abduction—Left	268.2	138.9	278.8	145.1	−0.836	0.404	0.50	0.37	0.61	102.6	37.52	27.61	62.50
	Hip Abduction—Right	257.0	132.8	269.2	136.1	−1.266	0.208	0.51	0.38	0.62	94.4	35.89	26.83	58.25
	Hip Adduction—Left	285.9	157.2	299.2	170.8	−1.375	0.171	0.61	0.50	0.71	101.4	34.67	28.16	49.22
	Hip Adduction—Right	276.6	157.7	285.4	163.4	−1.167	0.245	0.62	0.51	0.71	97.1	34.55	28.19	48.71
	Hip Internal rotation—Left	209.1	117.3	219.7	121.8	−1.441	0.152	0.62	0.51	0.71	72.8	33.95	28.03	47.11
	Hip Internal rotation—Right	215.9	119.5	221.0	119.6	−0.784	0.434	0.56	0.43	0.66	79.2	36.24	28.28	54.91
	Hip External rotation—Left	244.5	257.8	229.8	123.7	1.112	0.264	0.72	0.61	0.79	77.7	32.78	27.78	42.33
	Hip External rotation—Right	236.9	129.1	225.3	122.1	1.425	0.156	0.69	0.60	0.76	79.6	34.46	29.86	44.02
	Hip Flexion—Left	418.9	283.9	427.7	289.9	−0.799	0.426	0.58	0.45	0.69	193.5	45.70	35.38	69.83
	Hip Flexion—Right	444.1	290.6	446.4	283.1	0.343	0.732	0.67	0.56	0.76	170.0	38.18	31.90	51.54
	Hip Extension—Left	460.3	321.9	487.9	289.1	−1.421	0.158	0.53	0.40	0.64	207.0	43.67	33.10	69.40
	Hip Extension—Right	534.9	303.3	518.1	313.4	0.271	0.786	0.63	0.51	0.72	191.4	36.34	29.70	51.05

SD—standard deviation; t—T-test statistics; p—statistical significance; CI—confidence interval; TE—typical error; CV—coefficient of variation; RTD—rate of torque development

Table 2. Descriptive and normality analysis of asymmetry variables.

Asymmetry (%)	Mean	SD	S-W
Functional leg length	0.76	0.62	0.002
Single-leg Countermovement Jump— height	11.12	8.36	0.005
Single-leg Countermovement Jump— PF	4.77	4.40	0.000
Single-leg Countermovement Jump—PP	7.06	5.98	0.001
Single-leg Horizontal Jump—distance	4.60	3.19	0.051
Single-leg Lateral Jump—distance	4.82	3.70	0.001
Single-leg Triple Jump—distance	3.48	2.67	0.005
Hip Abduction—PT	3.68	3.15	0.001
Hip Abduction—RTD	11.23	9.67	0.000
Hip Adduction—PT	5.59	4.77	0.001
Hip Adduction—RTD	10.72	10.34	0.000
Hip External Rotation—PT	7.90	5.82	0.000
Hip External Rotation—RTD	13.18	8.83	0.000
Hip Internal Rotation—PT	11.52	7.17	0.150
Hip Internal Rotation—RTD	13.17	9.55	0.020
Hip Extension—PT	11.01	8.92	0.000
Hip Extension—RTD	30.56	21.79	0.031
Hip Flexion—PT	9.86	8.36	0.000
Hip Flexion—RTD	40.35	20.42	0.619
Trunk Lateral Flexion—PT	12.81	9.61	0.013
Trunk Lateral Flexion—ROM	8.98	5.94	0.054
Hip Abduction—ROM	8.94	5.72	0.165
Hip Adduction—ROM	8.83	6.73	0.002
Hip Flexion—ROM	5.91	6.24	0.000
Hip Extension—ROM	12.80	10.95	0.000
Hip External Rotation—ROM	13.00	14.10	0.000
Hip Internal Rotation—ROM	13.54	10.57	0.002
Hip extension/flexion strength ratio (left leg)	1.32	0.33	0.183
Hip extension/flexion strength ratio (right leg)	1.30	0.25	0.011
Hip abduction/adduction strength ratio (left leg)	1.08	0.19	0.048
Hip abduction/adduction strength ratio (right leg)	1.07	0.20	0.010
Hip internal/external rotation strength ratio (left leg)	1.13	0.27	0.266
Hip internal/external rotation ratio (right leg)	1.18	0.26	0.279
Trunk extension/flexion strength ratio	1.27	0.27	0.331
T-test	9.10	0.50	0.013

SD = standard deviation, S-W = Shapiro–Wilks tests, PF = peak force, PP = peak power, RTD = rate of torque development, ROM = range of motion.

Table 3. Peak torque and Rate of torque development differences (Mann–Whitney U test).

Asymmetry (%)	PT Mean ± SD	RTD Mean ± SD	*p*-Value	Effect Size
Hip abduction	3.68 ± 3.15	11.23 ± 9.67	0.000	0.56
Hip adduction	5.59 ± 4.77	10.72 ± 10.34	0.002	0.23
Hip external rotation	7.90 ± 5.82	13.18 ± 8.83	0.001	0.27
Hip internal rotation	11.52 ± 7.17	13.17 ± 9.55	0.514	0.01
Hip extension	11.01 ± 8.92	30.56 ± 21.79	0.000	0.38
Hip flexion	9.86 ± 8.36	40.35 ± 20.42	0.000	1.00

PT = peak torque, RTD = rate of torque development; SD = standard deviation.

Table 4. Hip strength ratio differences between left and right leg (Mann–Whitney U test).

Hip Strength Ratio	Left Leg Mean ± SD	Right Leg Mean ± SD	*p*-Value	Effect Size
Extension/Flexion	1.32 ± 0.33	1.30 ± 0.25	0.779	0.00
Abduction/Adduction	1.08 ± 0.19	1.07 ± 0.20	0.826	0.00
Internal/External Rotation	1.13 ± 0.27	1.18 ± 0.26	0.218	0.03

SD = standard deviation

A six-variable regression model explained 48% ($R^2 = 0.48$; $p < 0.01$) of the variation in the T-test performance (Table 5). T-test time was predicted by left hip internal/external rotation strength ratio ($\beta = -0.58$; $p < 0.01$) and inter-limb asymmetries in hip abduction RTD ($\beta = -0.38$; $p = 0.01$), hip flexion ROM ($\beta = 0.32$; $p = 0.03$), functional leg length ($\beta = 0.31$; $p = 0.02$), SLTJ distance ($\beta = 0.29$; $p = 0.04$), and peak torque during trunk lateral flexion ($\beta = 0.27$; $p = 0.05$).

Table 5. Final regression model with six independent variables (dependent T-test).

Depended Variable	Independent Variable	B	Beta	R^2	*p*-Value
T-test (s)	-	-	-	0.48	<0.001
-	Left hip internal/external rotation strength ratio	−1.08	−0.58	-	0.00
-	Asymmetry in hip abduction RTD (%)	−0.02	−0.38	-	0.01
-	Asymmetry in hip flexion ROM (%)	0.03	0.32	-	0.03
-	Asymmetry in functional leg length (%)	0.25	0.31	-	0.02
-	Asymmetry in SLTJ (%)	0.06	0.29	-	0.04
-	Asymmetry in peak force during trunk lateral flexion (%)	0.01	0.27	-	0.05

RTD—rate of torque development; ROM—range of motion; SLTJ—single-leg triple jump.

4. Discussion

The aims of the present study were twofold: (a) to profile elite basketball players in different local strength and range of motion asymmetries of hip and trunk region, global power asymmetries in horizontal and vertical jumping and (b) to quantify the relationship of these asymmetries with COD performance. Results showed different magnitudes of asymmetries among tests, body regions, and parameters.

Regarding the magnitude of asymmetry scores reported in this study, largest asymmetries were found in hip RTD (10.72–40.35%), which were significantly larger (except internal rotation) than peak force asymmetries of different hip action (3.68–11.52%) (as shown in Table 2). Compared to local peak torque asymmetries, rate of torque development showed to be a more sensitive parameter for assessment of asymmetries. That is in accordance with findings of Sarabon et al. [23], who reported that the RTD showed larger magnitudes of asymmetries than peak torque during unilateral isometric knee flexion and extension.

To our knowledge, only one study profiled hip strength ratios in professional athletes using fixed point dynamometer [31]. Although study was done on Australian football players, it detected similar results in flexion/extension mean ratio (0.8) as our study (1.3). Moreover, their mean internal/external ratio was 1.15 which is in accordance to our values (1.13 and 1.18 for left and right leg).

They observed a hip adductor/abductor ratio of 1.05 which is much different from our abduction/adduction ratios (1.08 and 1.07), such differences can be attributed to sport specificity of ball kicking in Australian football.

Our results are also showing various magnitudes in hip range of motion asymmetries (5.91–13.54%), with largest being found for extension (12.80 ± 10.95%), internal rotation (13.54 ± 10.57%), and external rotation (13.00 ± 14.10%). Although some research indicates that there are significant differences in hip ROM between the dominant and non-dominant leg in football players [32], a direct comparison of results is limited because authors have not reported asymmetry indexes.

Mean asymmetry in functional leg length was 0.76 ± 0.62%. To our knowledge, studies that assessed asymmetries in anthropometry had not used the functional leg length to investigate the relationship with performance instead, they had utilized other anthropometric measurements, such as knee and ankle joint width [33] or lean mass asymmetry [34]. Although, there is no past research to compare our results with, a review of Knutson et al. [35] set a threshold of normal functional leg length discrepancy at 2 cm. The mean absolute asymmetry in our study was 0.9 cm, which is thus considered as normal leg length variation.

Inter-limb asymmetries in vertical jumping parameters (4.77–11.12%) showed larger values compared to horizontal jumps (3.48–4.60%), which is in accordance with research conducted by Lockie et al. [15], who reported SLCMJ mean inter-limb asymmetries at 10.4 % and only 5.4% and 3.3% for horizontal jumps (SLHJ and SLLJ). Similar results were reported by Bishop et al. [36] who found larger inter-limb asymmetries in SLCMJ (12.5%) compared to SLHJ (6.8%). Both of these studies were conducted on football players, which indicates that the variability between the testing methods might be substantially higher than the variability between the athletic populations. With that in mind, it can be suggested that vertical jumping is more sensitive for detecting asymmetries than horizontal jumping.

While all of our maximal strength measures showed an excellent reliability (displayed in Table 1), the explosive strength (rate of torque development) were only moderately reliable. As the structured strength and conditioning training as well as the experience level contribute to reliability of data [37], our data can be interpreted with confidence. In the past years, there has been a lot of debate about defining normal asymmetry threshold, most common one being 10%, but different authors suggested values from 5% to 20% [6]. Taking all that into consideration, variability of asymmetry results in our data shows that asymmetry magnitude is dependent on the specific movement, test and parameter which indicates that a unifying asymmetry threshold cannot be established.

Regression analysis revealed a relationship between asymmetries and performance: six variable model explained 49% of T-test performance variance. Independent variable Beta scores (0.27–0.58) show a small to medium individual relationship between different type of asymmetry and COD performance. Although several studies (including the present study) observed negative influence of asymmetries on COD performance, a number of studies identified contradicting evidence. Lockie et al. [10] showed negative influence ($r = 0.638, 0.669$, $p < 0.01$) of isokinetic concentric (60°/s, 180°/s, 240°/s) and eccentric (30°/s) knee strength asymmetries and COD performance (assessed with T-test). The study of Coratella et al. [11] reported similar results of association between knee strength asymmetries in slow (30°/s) and fast (300°/s) contractions and COD performance (T-test and 180° turn test). On the other hand, the relationship between COD performance (180° turn test) and strength asymmetries tested with the whole kinetic chain movements (e.g., IMTP) has not been detected [12,13]. This observation could be explained by local strength asymmetries show higher magnitudes. Negative influence of asymmetry in vertical drop jump height and COD performance (180° turn test) ($r = 0.66$, $p < 0.01$ and 0.52, $p < 0.05$; depending on the side of the turn) was found by Bishop et al. [21]. Also, using horizontal jumps to assess asymmetries, Madruga-Parera et al. [38] found much lower correlations ($r = 0.32$ and 0.31, $p < 0.05$) between asymmetry in horizontal jumping length (SLLJ) and COD performance (V-cut and 180° turn test). Such a relationship was not found by Lockie et al. [15], who did not observe significant correlations between asymmetry in vertical (SLCMJ height) and horizontal (SLHJ and SLLJ distance) jumping and COD performance (T-test and 180° turn test). Similarly, Loturco et al. [18] suggested that asymmetry in various parameters during single-leg squat jump and CMJ do not influence COD performance (zig-zag test). The study conducted by Maloney et al. [22] is probably the most comparable to ours, it showed that stiffness and asymmetry in single-leg drop jump explained 63% variance of COD performance (2 × 90°cut test). However, they used just one type of asymmetry as the secondary predictor, while the stiffness during drop jump was main predictor in the model.

Our model consists of several independent variables, each representing a different type of asymmetry and together showing a significant relationship with COD performance. This is important because findings indicated an independent nature of asymmetry [39]. The most important finding of this study is the connection between asymmetry and COD performance, but also that testing large variety of asymmetry types is needed to gain a more complete understanding of athlete asymmetry and its relationship to performance.

Certain limitations of this study should be noted. The main limitation is the modest reliability of hip explosive strength measure, however, we find this acceptable as RTD is a highly variable parameter. Moreover, a slightly larger sample size would have been useful in the linear regression analyses, as the best model included a relatively large number of predictor variables.

5. Conclusions

This study was conducted to explore asymmetries in local strength, vertical jumping and ROM, and to investigate whether these asymmetries are related to COD performance in healthy elite-basketball players. A substantial variability among asymmetries in different tests was noted. This implies that coaches and physiotherapists should not rely exclusively on the <10 % threshold when they are deciding on the athletes return to play, or planning interventions for reducing asymmetries. In particular, it is expected for RTD asymmetries to be larger than maximal strength (i.e., peak torque) asymmetries. In the attempt to elucidate which asymmetries are more relevant for performance, specifically to the COD ability, we performed linear regressions which showed more than one type of asymmetry is should be considered in the analyses to sufficiently explain the COD performance. Notably, the best model for predicting COD performance included both maximal strength and RTD asymmetry, both hip and trunk asymmetry, one vertical jump asymmetry, one ROM asymmetry, as well as asymmetry in functional leg length. Therefore, interventions should likely target multiple types of asymmetries when trying to improve COD performance. We encourage practitioners to use a wide testing battery to test different aspects on local and global level of the body to obtain a clearer picture of athletes' asymmetries.

Author Contributions: Conceptualization, F.U. and N.Š.; Data curation, F.U.; Formal analysis, F.U.; Funding acquisition, N.Š.; Investigation, F.U.; Methodology, N.Š.; Project administration, N.Š.; Resources, N.Š.; Software, N.Š.; Supervision, N.Š.; Validation, F.U. and N.Š.; Writing—original draft, F.U. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The authors would like to thank the athletes and management from the basketball clubs participating in this study. Additionally, many thanks to the research assistants who helped at testing.

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