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

Martin Zorko 1,*, Karmen Hirsch 2, Nejc Šarabon 3,* and Matej Supej 2,*

1 Clinical Institute of Occupational, Traffic and Sports Medicine, University Medical Centre Ljubljana, 1000 Ljubljana, Slovenia
2 Faculty of Sport, University of Ljubljana, 1000 Ljubljana, Slovenia; laksmipria@gmail.com
3 Faculty of Health Sciences, University of Primorska, Polje 42, 6310 Izola, Slovenia
* Correspondence: zorkom@gmail.com (M.Z.); nejc.sarabon@fvz.upr.si (N.Š.); matej.supej@fsp.uni-lj.si (M.S.)

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

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.](image)

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](image_url)

**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](image)

**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](image)

**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.](image)

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.](image)
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 \(V_{\text{ML}}\) 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 \(A_{\text{AP}}\) values between different ski widths \((F = 4.89; p < 0.05; \eta^2 = 0.31)\) (Figure 7).

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

**Figure 7.** CoP amplitude in anteroposterior direction \((A_{\text{AP}})\) 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.

**Figure 8.** CoP amplitude in mediolateral direction \((A_{\text{ML}})\) in a prefatigued state (before F) and at different times after fatigue (after F) with two different ski waist-widths. * depicts statistically significant difference 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 \(A_{\text{ML}}\) was significantly higher only immediately after fatigue \((t = -3.44; p < 0.01; d = 0.52)\).

Significant differences were observed in \(M_{\text{FAp}}\) with different ski widths \((F = 5.93; p < 0.01; \eta^2 = 0.37)\). The \(M_{\text{FAp}}\) 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](image_url)

**Figure 9.** The mean frequency of the power spectrum of CoP in the anteroposterior direction \((M_{\text{FAp}})\) 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 \(M_{\text{FAp}}\) 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 \(M_{\text{FAp}}\) 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 \(M_{\text{FML}}\) 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).

\(M_{\text{FML}}\) 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 \(M_{\text{FML}}\) 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 \(M_{\text{FML}}\) 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.

Funding: This research was funded by the Slovenian Research Agency (L5-1845, L54142, and P5-0147).

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.

Conflicts of Interest: The authors declare no conflict of interest.

References


**Publisher’s Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).