

How does the ski boot affect human gait and joint loading?

Karol Lann vel Lace, Michalina Błażkiewicz

Faculty of Rehabilitation, Józef Piłsudski University of Physical Education, Warsaw, Poland

Abstract

Study aim: To investigate the effect of wearing ski boots on kinematic and kinetic parameters of lower limbs during gait. Furthermore, loads in lower limb joints were assessed using the musculoskeletal model.

Material and methods: The study examined 10 healthy women with shoe size 40 (EUR). Kinematic and kinetic data of walking in ski boots and barefoot were collected using a Vicon system and Kistler plates. A musculoskeletal model derived from AnyBody Modeling System was used to calculate joint reaction forces.

Results: Wearing ski boots caused the range of motion in the knee joint to be significantly smaller and the hip joint to be significantly larger. Muscle torques were significantly greater in walking in ski boots for the knee and hip joints. Wearing ski boots reduced the reaction forces in the lower limb joints by 18% for the ankle, 16% for the knee, and 39% for the hip.

Conclusions: Ski boot causes changes in the ranges of angles in the lower limb joints and increases muscle torques in the knee and hip joints but it does not increase the load on the joints. Walking in a ski boot is not destructive in terms of forces acting in the lower limb joints.

Keywords: Kinematics – Kinetics – Joint loading – Ski-boot – Gait

Introduction

Ski boots are one of the most important parts of skiing equipment. They are crucial in transferring load from the skier to the skies through the bindings, which allows the user to maintain control over skies. They allow the skier to perform maneuvers such as downhill skiing, turning, stopping, and jumping. Their function requires the construction to be stiff and properly adjusted to the athlete's limbs, which also protects the foot, ankle, and lower tibia.

Over the years, boots have developed into the modern high spoiler plastic boots with buckles. Stiffer and lean-forward design helped reduce the incidence of ankle and tibial fractures, but increased the risk of knee injuries, particularly ACL rupture, due to the valgus or varus opening mechanisms [4]. Furthermore, the continuous knee flexion causes the muscular imbalance of the lower limb [18]. It might be speculated that knee misalignment, caused by the ski boot, places extra pressure on the muscles around the knee and possibly exaggerates muscle imbalances and patella grinding [6, 8].

Ski boots are designed for skiing but walking in those boots is not easy. Normal gait is rhythmic and

consists of propulsive and retropulsive movement of the lower limbs. Unrestricted ankle movement is required to walk freely and efficiently. Usually, ankle range of motion might be restricted as a result of injuries such as ankle sprain [20] or ankle fracture [12]. During the mid-stance and through terminal stance phases of normal gait, maximal dorsiflexion of about 10° is maintained. The permanent change in the ankle position or restriction of motion may affect other joints and cause compensations [14]. It was also proved that reduced ankle motion causes a 50% reduction in ankle push-off power and work, leading to up to 50% greater net metabolic expenditure [9].

To our knowledge, no studies have analyzed gait in ski boots, even though skiers often have to walk certain distances in ski boots, which are not designed for walking. An extensive body of research has been devoted to the effect of ski boots on postural control [2, 13, 17], ski boot design, its effect on injury locations [3] and factors affecting skiing performance [5, 10]. Ski boots are designed to transfer movements into skis while supporting and protecting the feet, ankles, and lower legs. In order for the boots to transfer forces effectively, they have to be stiff and restrict the movement in ankles. This stiffness and the lack of movement makes it a lot harder to walk in

ski boots than in normal shoes. Therefore, the aim of the study was to investigate the effect of wearing ski boots on kinematic and kinetic parameters of lower limbs during gait. Furthermore, using the musculoskeletal model, an attempt was made to assess the load in the joints of the lower limbs.

Materials and methods

Participants and procedures

This study examined ten healthy women aged 20.7 ± 1.64 years with a mean body height of 1.71 ± 0.06 m, body weight of 65.2 ± 4.1 kg, and shoe size 40 (EUR). Participants reported no lower limb injuries and had experience in skiing of at least 5 years. The participants gave written consent to participate in the experimental procedures, which were approved by the University Research Ethics Committee. Atomic Hawx Ultra 115 S W 2019 ski boots were used in the tests (Fig. 1). These are the stiffest women's ski boots in the Hawx Ultra lightweight series. Shoe weight was 1510 g. The Power Shift solution allowed the shoe angle to be adjusted up to 15 (default), which was constant over the test cycle.

Prior to the experiment, anthropometric measurements were taken for each subject. Next, fifteen spherical markers were placed at anatomical landmarks according to the biomechanical lower body Plug-in-Gait (SACR) model available in the motion capture system (Vicon Motion

Systems Ltd, UK). Two force plates (Kistler Holding AG, CH) embedded into the floor were used to measure ground reaction force data at a sampling rate of 1000 Hz. A motion capture system consisting of nine infra-red cameras was employed to collect kinematic data at a sampling rate of 100 Hz. The force plates were synchronized with the motion capture system. Before the trials, both systems were calibrated according to the manufacturer's recommendations. Each subject performed three trials during the two different gait conditions (barefoot gait and gait in ski boots at self-selected speed).

Data analysis

The kinematic and kinetic data of one trial for each barefoot gait and gait in ski boots of each participant were imported into the AnyBody 7.0 (AnyBody Technology, Denmark) software. The musculoskeletal model MoCap-Model-LowerBody (AMMR 1.6.6) was used to calculate lower limb joints reaction forces. In this model, each leg had seven degrees of freedom: three in the hip joint, one in the knee joint, one in the ankle joint, one in the subtalar joint, and one in the patellar movement. Each leg was composed of 55 muscles divided into 159 muscle-tendon actuators. Mass, moments of inertia, and muscle geometry of all segments were modeled according to the morphological dataset for the lower limbs provided by Klein Horsman et al. [11]. The model was scaled to match each participant's anthropometric characteristics [1]. Inverse dynamics analysis was performed to calculate muscle force distribution and joint reaction forces [16]. The analysis was based on the values of angles, muscle torques, ground reaction forces, and joint reaction forces. Parametrization was performed for the obtained profiles (Fig. 2A-C, 3A-C) by selecting characteristic minimum and maximum values for the curve. Net force was additionally calculated for joint reaction forces ($\sqrt{AP^2 + ML^2 + PD^2}$, AP: anteroposterior, ML: mediolateral, PD: proximal-distal). Joint reaction forces were normalized to body weight (xBW). The statistical analysis was conducted using Statistica 12 (StatSoft Inc., USA). The significance level was set at 0.05. Not all parameters met the requirements for normality in the data using the Shapiro-Wilk test. For this reason, and because of the small number of participants, the non-parametric Wilcoxon test was used to show statistically significant differences between the analyzed gait. A comparative analysis was also conducted between the individual joints to determine those exposed to the highest loads during free walking and during walking in ski boots. Only the maximum values of muscle torques and ground reaction forces were taken into account during the analysis. Effect size was calculated using GPower 3.1 (University of Dusseldorf, Dusseldorf, Germany) and was at the level 0.9999.



Figure 1. Ski-boot – Atomic Hawx Ultra 115 S W 2019

Results

Comparative analysis between different types of gaits

Joint angles and torques

For each joint, statistically significant differences between gaits were found for both kinematic and kinetic parameters (Fig. 2A-C). Wearing the ski boot caused the ankle joint to be in constant dorsiflexion (Fig. 2A). Therefore, the ankle range of motion (max-min) in free walking was $32^\circ \pm 2^\circ$, while in walking in ski boots, it was significantly ($p = 0.0033$) lower and was $17^\circ \pm 3^\circ$. The greatest effect of a ski boot was observed for the knee joint. All characteristic values were significantly higher for walking in ski boots both in the support and swing phases. The first 20% of the gait cycle was characterized by flexion (max1) of up to $29.6^\circ \pm 7.8^\circ$ during walking in ski boots and was significantly ($p = 0.0033$) higher than during free walking ($21.2^\circ \pm 6.6^\circ$). The minimum values for free walking in the terminal stance phase (30–50%) of the gait cycle (GC) reached on average 0.5° , and were significantly ($p = 0.0033$) lower than those obtained in this phase during walking in ski boots ($14.3^\circ \pm 7^\circ$). In the transfer phase, the values in walking in ski boots reached $68.5^\circ \pm 8.3^\circ$ and were 15% higher than those in free walking. In the hip joint, a significantly ($p = 0.0001$) larger flexion was observed only in the terminal swing phase during walking in ski boots $45.85^\circ \pm 4.7^\circ$ vs. $34.8^\circ \pm 4.7^\circ$.

The analysis of the effect of ski boots on the values of muscle torques (Fig. 2B) revealed no significant differences in the shape of the curves for the ankle joint. As in the case of the angular profiles, the greatest differences were observed for the knee joint in the whole gait cycle domain. In the first 20% of the gait cycle, i.e. when the heel is placed on the ground, twice higher flexion values of 1.02 ± 0.12 Nm/kg were reached during walking in ski boots compared to those achieved in free walking (0.46 ± 0.13 Nm/kg). In the terminal stance phase (30–50%) of GC, the values reached 0.37 ± 0.29 Nm/kg for walking in ski boots, and -0.14 ± 0.1 Nm/kg during free walking, confirming the presence of continuous flexion due to the presence of the ski boot. In the pre-swing phase (50–60%) of the gait cycle, the highest flexion values of 0.74 ± 0.09 Nm/kg were achieved in free walking, while at the same time, muscle torques were 0.38 ± 0.23 Nm/kg for walking in ski boots. For hip muscle torques, significantly higher values were recorded for walking in ski boots, with 1.00 ± 0.4 Nm/kg in the first 20% of the gait cycle compared to those achieved for free walking i.e. 0.51 ± 0.18 Nm/kg. The same is true for the minimum values, where the values were significantly lower than those obtained for walking in ski boots, with -0.75 ± 0.13 Nm/kg compared to -0.50 ± 0.15 Nm/kg for free walking. All the above-

mentioned differences were statistically significant at the level ($p = 0.0033$).

Wearing ski boots had also an effect on the components of ground reaction forces (Fig. 2C). Significantly higher values were found for the mediolateral ($p = 0.0015$) and anteroposterior ($p = 0.0013$) components of walking in a ski boot. Furthermore, for the vertical component, the values were 15% lower during walking in ski boots (mainly in the pre-swing phase), which may indicate a poor take-off.

Joint reaction forces

Considering the reaction forces in individual lower limb joints, it is worth noting that for the knee and hip joints, there are three peak values in each plane and for the net force curve i.e. two maxima and one minimum (Fig. 3A, B). The first maximum value was found in the loading response /mid-stance phase (0–30%) of the gait cycle whereas the second was observed in the terminal stance phase (30–50%). Minimum values occurred in the mid-stance phase (10–30%) of GC. Only one maximum peak was observed in each plane and for the net force curve for the knee joint (Fig. 3C). The Wilcoxon test revealed statistically significant differences between the curves of reaction forces in the lower limb joints for free walking and walking in ski boots.

Considering the hip joint (Fig. 3A) in the first 30% of the gait cycle, significantly ($p = 0.0044$) higher peaks were recorded for all components (except for A/P) in free walking. For the terminal stance phase, statistically significant differences were observed only for the P/D and A/P components, which resulted in significant differences also for the net reaction force in the hip joint. It was noted that the maximum values for the net hip joint reaction force (max1, max2) are on average 38.4% lower than those obtained in free walking. Analysis of the net knee reaction force showed statistically significant differences for the peaks present in the mid-stance and terminal stance phases, which is mainly influenced by the proximal-distal component. In the mid-stance phase, the values for walking in ski boots (2.62 ± 0.79 xBW) are significantly ($p = 0.0035$) higher for free walking (1.98 ± 0.26 xBW). In the terminal stance phase, on the other hand, the values decrease significantly ($p = 0.0182$) for walking in ski boots (5.91 ± 1.04 xBW) compared to free walking (7.02 ± 0.34 xBW). For the ankle joint and walking in ski boots, the extremes obtained in each plane and their net value were on average 24.6% lower than the respective measures for free walking. In conclusion, for all the components of the reaction forces in the joints, lower or significantly lower values were obtained for walking in ski boots. The main components where the highest values were recorded were the proximal-distal component, followed by the anteroposterior and mediolateral components.

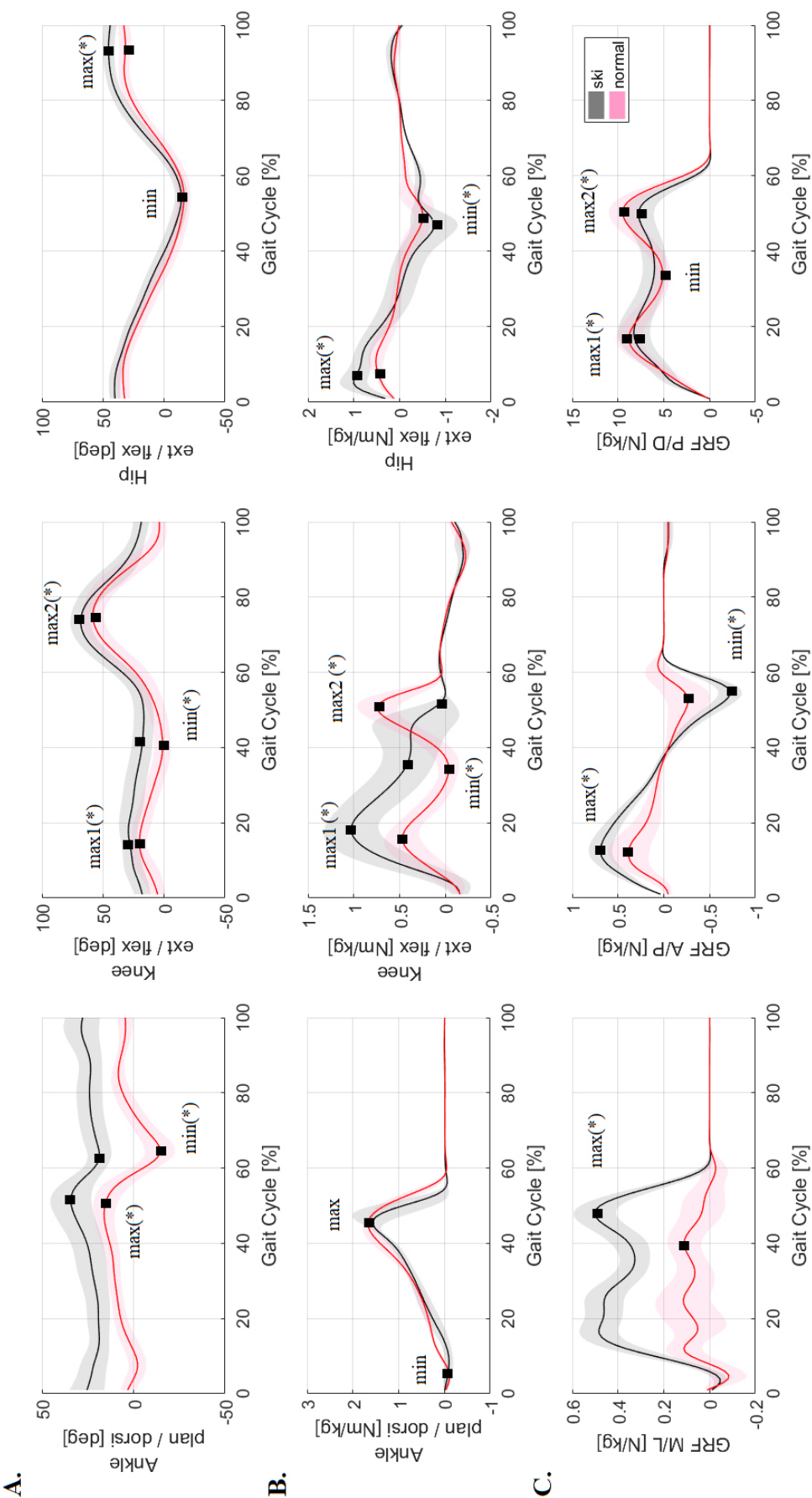


Figure 2. Parametrization, extreme values for (A) angular profiles, (B) muscle torques in lower limb joints, (C) ground reaction forces during free walking and walking in ski boots, where: red line is the mean for free walking, black line is the mean for walking in ski boots, and * denotes statistically significant differences ($p \leq 0.05$)

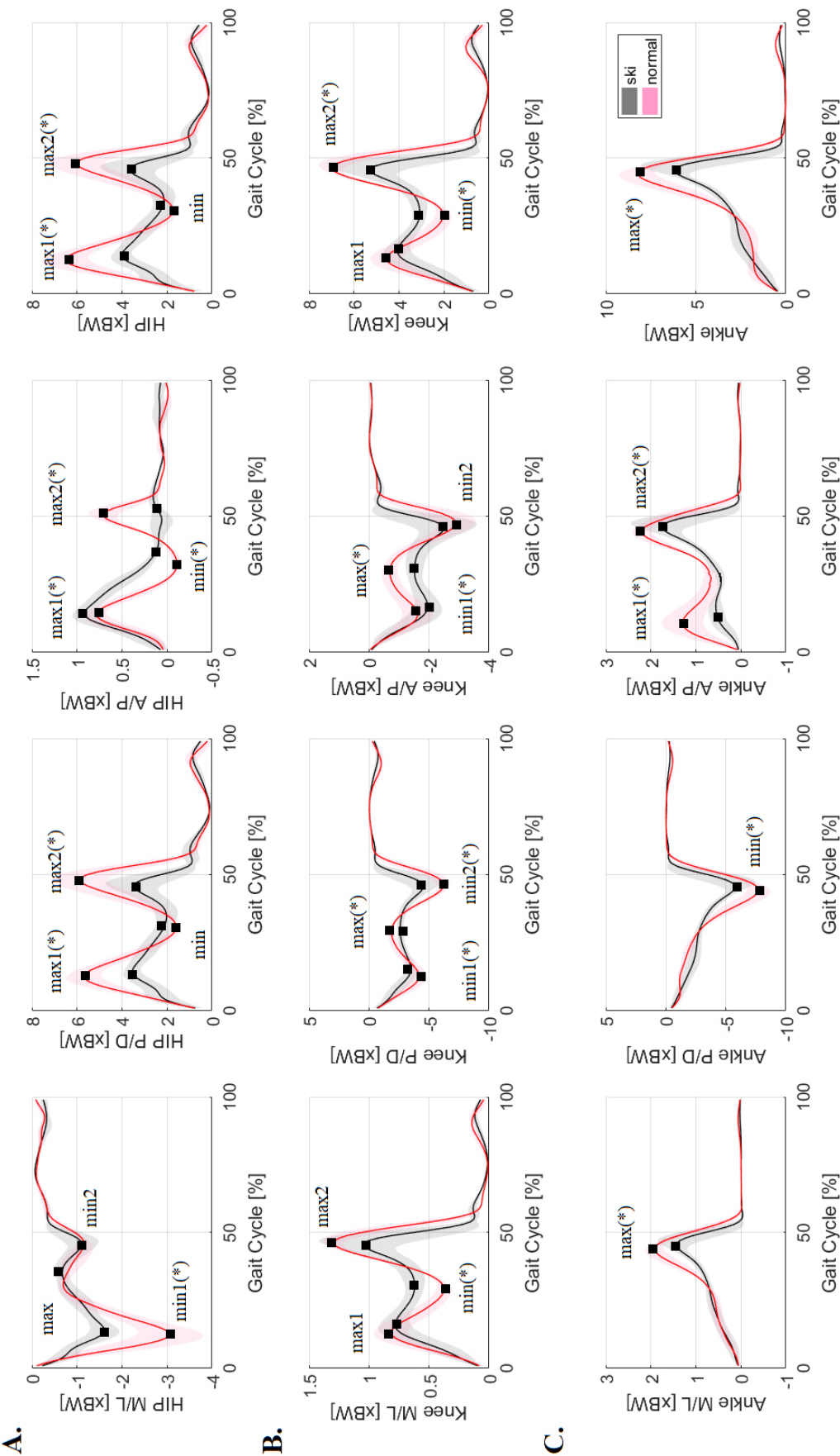


Figure 3. Components of joint reaction forces in (A) hip, (B) knee, (C) ankle in the frontal (M/L), transverse (P/D) and sagittal (A/P) planes and the net force for free walking and walking in ski boots, where: red line is the mean for free walking, black line denotes the mean for walking in ski boots, and * denotes statistically significant differences ($p \leq 0.05$)

Comparison of the loads between the joints

In order to compare the loads occurring in the lower limb joints in the gait cycle domain, maximum values were found for the net reaction forces in the joints and for the muscle torques. It was demonstrated that for muscle torques, the highest average values were achieved successively for: ankle (1.66 ± 0.10 Nm/kg), knee (0.74 ± 0.09 Nm/kg), and hip (0.51 ± 0.18 Nm/kg) in free walking. The differences between the values were statistically significant ($p = 0.0013$) for all combinations. Furthermore, the highest values during walking in ski boots were achieved for the ankle (1.56 ± 0.14 Nm/kg), followed by the knee (1.02 ± 0.12 Nm/kg), and hip (1.00 ± 0.4 Nm/kg). The differences were statistically significant ($p = 0.0033$) only for combinations of ankle with knee and hip.

Analysis of the joint reaction forces revealed that in free walking, the highest load can be observed in the ankle (8.27 ± 0.75 xBW), knee (7.02 ± 0.34 xBW), and hip (6.60 ± 0.77 xBW). For walking in ski boots, the order was the same, but the values were much smaller: ankle: (6.79 ± 0.77 xBW), knee: (5.91 ± 1.04 xBW) and hip: (4.03 ± 0.38 xBW). The differences were statistically significant ($p = 0.0013$) for all combinations, except for the comparison of ankle and knee, where $p = 0.0033$.

Discussion

The aim of this study was to investigate the effect of wearing ski boots on kinematic and kinetic parameters of lower limbs during gait. Furthermore, loads in lower limb joints were assessed using the musculoskeletal model.

Human locomotion results from the integration of physiological and biomechanical factors such as external devices. Ankle-foot orthoses (AFOs) or specific sports shoes such as ski boots are designed to limit ankle joint mobility and are known to influence postural control [17] and gait, as shown in the present study. One of the problems that confront skiers is walking around in ski boots. This activity is usually performed for a short time but is often necessary and uncomfortable.

Wearing ski boots restricts ankle joint movements similar to wearing orthoses. Walker orthoses, which look like ski boots, are usually set in the neutral position, opposite to ski boots, which maintain ankle joints in dorsiflexion of ca. 12–15 degrees [21]. Vanderpool, Collins and Kuo [19] analyzed gait in Walker orthoses. They showed that immobilization of the ankles resulted in changes in joint kinematics, torques, and powers. In terms of kinematics, knee, and hip joint angles were within the normal range, which is inconsistent with the findings of the present study. Furthermore, Gulgin, Hall, Luzadre and Kayfish [7] analyzed bilateral gait with and without walking boots and found a significant increase in the hip (6%) and knee flexion

angle (5%) compared to free walking. In the present study, we obtained similar results. Ski boots set ankles in dorsiflexion throughout the gait cycle, which translated into a reduced range of motion in the knee joint ($54.5^\circ \pm 1.6^\circ$) and a significantly greater range of motion in the hip joint ($60.7^\circ \pm 0.4^\circ$) compared to free walking, where the range of motion was $59.8^\circ \pm 2.1^\circ$ for the knee and $51.2^\circ \pm 0.6^\circ$ for the hip. The differences between the results obtained in the present paper and those published by Vanderpool et al. [19] may be caused not only by the ankle position but also by the differences in sole design. Walker's sole is curved to ease the roll-over phase and decrease gait alteration. The sole of a ski boot is formed of a rigid toe and heel portion, which makes it difficult to walk, especially in loading response and pre-swing phases.

The analysis of the effect of ski boots on the values of muscle torques in the lower limb joints and joint reaction forces reveals that the results were similar to those published in the papers by Gulgin et al. [7], Pollo et al. [15] and Zhang et al. [21]. In this study, no significant differences were found in the shape of the curves for the ankle joint. As in the case of the angular profile, the greatest differences were observed for the knee joint. Its highest value was 1.02 ± 0.12 Nm/kg and was twice as high as in free walking. The maximum value of muscle torques in the hip joint was also high and was 1.00 ± 0.4 Nm/kg in the first 20% of the gait cycle compared to those achieved for free walking (0.51 ± 0.18 Nm/kg). Wearing ski boots had also an effect on the components of ground reaction forces, with significantly higher values found for the mediolateral and anteroposterior component of walking in a ski boot. Furthermore, for the vertical component, the values were 15% lower during walking in ski boots (mainly in the pre-swing phase), which may indicate a poor take-off caused by the presence of a rigid heel portion in soles of ski boots. Ankle fixation with ski boots appears to have some advantages compared to normal walking. Taking into account only the maximum values of net reaction forces in the lower limb joints, it can be observed that ski boots caused a significant reduction compared to free walking. Ski boots led to a reduction in the maximum net reaction force by 18% in the ankle, 16% in the knee joint, and 39% in the hip. In conclusion, it seems that although the ski boot causes changes in the ranges of angles in the lower limb joints and increases muscle torques in the knee and hip joints, which should result in an increase in activity and strength generated by the muscles of these joints, it does not increase the load on the joints. Therefore, it can be concluded that walking in a ski boot is not destructive in terms of forces acting in the lower limb joints.

A limitation of the study was that walking speed was not controlled and that the movement pattern was new. Subjects walked in the laboratory settings on a hard surface whereas skiers usually walk on snow, which means

that additional and not necessarily favorable external forces act on their bodies. Another limitation of this study is lacking of the analysis of kinematic (joint angles) and kinetic (joint torques) parameters in the frontal and transverse planes.

Conflict of interest: Authors state no conflict of interest.

References

- Andersen M., Benoit D., Damsgaard M., Ramsey D., Rasmussen J. (2009) Do kinematic models reduce the effects of soft tissue artefacts in skin marker-based motion analysis? An in vivo study of knee kinematics, *J. Biomech.*, 43: 268-273.
- Bohm H., Senner V. (2008) Effect of ski boot settings on tibio-femoral abduction and rotation during standing and simulated skiing, *J. Biomech.*, 41(3): 498-505.
- Burtscher M., Gatterer H., Flatz M., Sommersacher R., Woldrich T., Ruedl G., Hotter B., Lee A., Nachbauer W. (2008) Effects of modern ski equipment on the overall injury rate and the pattern of injury location in Alpine skiing, *Clin. J. Sport Med.*, 18(4): 355-357.
- Chaudhari A., Andriacchi T. (2006) The mechanical consequences of dynamic frontal plane limb alignment for non-contact ACL injury, *J. Biomech.*, 39(2): 330-338.
- Colbeck S. (1994) A review of the friction of snow skis, *J. Sports Sci.*, 12(3): 285-295.
- Davey A., Endres N., Johnson R., Shealy J. (2019) Alpine Skiing Injuries, *Sports Health*, 11(1): 18-26.
- Gulgin H., Hall K., Luzadre A., Kayfish E. (2018) 3D gait analysis with and without an orthopedic walking boot, *Gait Posture*, 59: 76-82.
- Hauser W., Schaff P., Sole B. (1987) Ski Boots: Biomechanical issues Regarding Skiing Safety and Performance, *Int. J. Sport Biomech.*, 3: 326-344.
- Huang T., Shorter K., Adamczyk P., Kuo A. (2015) Mechanical and energetic consequences of reduced ankle plantar-flexion in human walking, *J. Exp. Biol.*, 218(Pt 22): 3541-3550.
- Hydren J., Volek J., Maresh C., Comstock B., Kraemer W. (2013) Review of Strength and Conditioning for Alpine Ski Racing, *J. Strength Cond.*, 35(1): 10-28.
- Klein Horsman M., Koopman H., van der Helm F., Prose L., Veeger H. (2007) Morphological muscle and joint parameters for musculoskeletal modelling of the lower extremity, *Clin. Biomech.*, (Bristol, Avon), 22(2): 239-247.
- Lin C., Moseley A., Herbert R., Refshauge K. (2009) Pain and dorsiflexion range of motion predict short – and medium-term activity limitation in people receiving physiotherapy intervention after ankle fracture: an observational study, *Aust. J. Physiother.*, 55(1): 31-37.
- Noe F., Garcia-Masso X., Delaygue P., Melon A., Paillard T. (2020) The influence of wearing ski-boots with different rigidity characteristics on postural control, *Sports Biomech.*, 19(2): 157-167.
- Ota S., Ueda M., Aimoto K., Suzuki Y., Sigward S. (2014) Acute influence of restricted ankle dorsiflexion angle on knee joint mechanics during gait, *Knee*, 21(3): 669-675.
- Pollo F., Gowling T., Jackson R. (1999) Walking boot design: a gait analysis study, *Orthopedics*, 22(5): 503-507.
- Rasmussen J., Damsgaard M., Voigt M. (2001) Muscle recruitment by the min/max criterion – a comparative numerical study, *J. Biomech.*, 34(3): 409-415.
- Tchorzewski D., Bujas P., Jankowicz-Szymanska A. (2013) Body posture stability in ski boots under conditions of unstable supporting surface, *J. Hum. Kinet.*, 38: 33-44.
- Thomee R., Augustsson J., Karlsson J. (1999) Patellofemoral pain syndrome: a review of current issues, *Sports Med.*, 28(4): 245-262.
- Vanderpool M., Collins S., Kuo A. (2008) Ankle fixation need not increase the energetic cost of human walking, *Gait Posture*, 28(3): 427-433.
- Youdas J., McLean T., Krause D., Hollman J. (2009) Changes in active ankle dorsiflexion range of motion after acute inversion ankle sprain, *J. Sport Rehabil.*, 18(3): 358-374.
- Zhang S., Clowers K., Powell D. (2006) Ground reaction force and 3D biomechanical characteristics of walking in short-leg walkers, *Gait Posture*, 24(4): 487-492.

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