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The effect of foot setting on kinematic and kinetic skiing parameters during giant slalom: a single subject study on a gold medalist Paralympic sit skier.

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Abstract:

Objectives: Aim of the work was to study the effect of monoski foot adjustment on kinematic and kinetic skiing parameters expressing skier's technique.

Design: The independent variable was the skier position with respect to bindings by acting on the position of monoski foot sole clamp. Front (F), Mid (M) and Rear (R) settings were adopted with intervals of 20 mm. Course time, skiing speed, Ground Reaction Forces (GRFs) magnitude and point of application as well as damper stroke were the dependent variables.

Method: A Paralympic monoski was equipped with a dynamometric binding plate to measure GRFs, roll and pitch moments. A Paralympic gold medalist (LW10-1) was involved. Skier trajectory and gates location were measured by a global navigation satellite system (GNSS) in steep and medium slope portions. The athlete performed two runs in a giant slalom course for each setting of the foot position.

Results: GRFs, center of pressure (COP) point of application and their variation consequent to foot setting were measured. Peak values up to 3.36 times the total weight and damper speed of 675 mm/s in compression were found. Fastest runs, highest peak loads and best subjective ratings were recorded with F setting. COP mean values were influenced by the nominal foot adjustments. GRFs in left turns were 54% larger than in the right turns.

Conclusions: The position of monoski foot sole clamp influenced kinematic and kinetic skiing with an overall better performance with the F setting. An asymmetric behavior of the skier between right and left turning occurred. Findings can support the optimization and design of monoskis for a wider dissemination of Paralympic alpine sit skiing.

Keywords: Paralympic alpine sit skiing, giant slalom, monoski adjustment, structural loads, kinematics, GNSS.

1. Introduction

Paralympic skiing is an emerging discipline not only in the Paralympic competitions but also in recreational skiing, with growing scientific attention mainly from physiological[1] and injury prevention points of view[2–5]. The dissemination of Paralympic skiing is a mission for several institutions and researchers[6,7]: the level of safety that Paralympic alpine skiing can ensure is crucial for the diffusion of the sport, its acceptance among the potential users, their coaches and the clinical staff. Statistics show that Paralympic alpine skiing can still be associated with upper limb trauma, mainly in combination with adverse ambient and snow conditions[4,5].

Monoskis are complex mechanical systems for which the design and tuning of the suspension system, the ergonomics of the seat and the personalized setup of the mass distribution influence the performance and safety of the skier[8]. Although few technical standards exist to ensure the safety and adaptability of such sport equipment[9], very limited data are available regarding the loads acting on the suspension of the monoski during recreational or competitive skiing. Conversely, in abled-bodied skiing, several studies investigated the intensity and distribution of loads acting on the binding of a skier during slalom turns[10], paying also attention to the effect skiing techniques or ski shape could have on kinematic and kinetic parameters[11–16].

On the relevance of the previous investigations, we aimed to study the effect of monoski foot adjustment on the kinematic and kinetic skiing parameters of an elite Paralympic skier to (i) collect information about dynamic loads acting on the monoski structure and (ii) investigate the effect of foot setting on skier's performance and subjective evaluation.

2. Methods

A Paralympic alpine monoski (Impulse Boost by Unicent GmbH, CH) was used for the tests: the athlete seated on a carbon shell customized to his anthropometry and connected to an aluminum frame (Figure 1.a). The frame connects to a suspension mechanism that includes a spring/damper shock absorber (FOX X2 - 9.5/3 in (241/76 mm)) and a special locking/unlocking system for lifting the seat in a higher position when the skier takes the chairlift. The foot sole component is shaped like a regular ski boot sole to fit into regular ski bindings. The suspension system connects to the foot sole via a pair of screws. The foot position can be adjusted within a 50 mm range in the anterior-posterior direction (Figure 1.a).

The monoski was equipped with a dynamometric binding plate[17] that enables to measure GRF acting in normal (GRF_z) and lateral (GRF_y) directions with respect to the ski plate. Moreover, it enables to measure the pitch moment acting about the Y axis (transverse to the skis longitudinal axis) (M_Y) and the roll moment acting along the X longitudinal ski axis (M_X). The binding plate consists of two customized strain gauged load cells of 15mm thickness that are attached to the ski and support the front toe component and the rear heel component of the binding (Figure 1.b). By measuring the front and rear GRFs in the Z direction at the binding toe and at a heel known position, the system returns the total GRF_Z acting normal to the foot sole and the total M_Y with respect to a reference point, as indicated in Figure 1.b. Knowing the span between the front and rear force components, the longitudinal location of the COP (COP_x) where the resultant GRF_Z is applied, can be measured instantaneously as shown in Figure 1.c.

The monoski damper was equipped with a waterproof magnetostrictive 75 mm stroke sensor from GET (Athena, IT): data from the stroke sensor and the dynamometric binding were collected at 1 kHz with a GET M 40 portable data logger (Athena, IT).

A Paralympic skier double gold medalist in giant slalom (LW10-1) that suffered from paraplegia (T5 lesion) and showed no upper abdominal function was involved in the study. The study was approved by the institutional review board and the skier signed an informed consent before testing.

The skier was equipped with a geodetic global navigation satellite system (GNSS). An antenna (Antcom G5Ant-2AT1, USA) was mounted on his helmet while the GNSS system (Javad Alpha-G3T, USA) was fixed to the seat, tracking GPS and GLONASS on frequency L1 and L2 and recording position signals at 50 Hz. A GNSS base station was mounted close to the start of the course (receiver: Javad Alpha-G3T, antenna: Javad GrAnt-G3T)[13]. Double differential phase measurements were calculated to determine the skier's position while speed was derived from position data[18]. The location of the gates was surveyed by the same GNSS carried by the skier. Course setting and slope characteristics were derived according to Gilgien et al.[19]. GNSS and dynamometric systems were synchronized by an external trigger.

Tests were performed in a giant slalom course set in Adelboden (CH). A Stöckli Laser GS FIS ski (length 188 cm, radius 25.5 m) was chosen by the skier: the Total Weight (TW) of the skier-monoski-instrumentation system was 1000 N. 22 gates were placed with a lateral offset of 6.3±0.8m and gate distance of 23.6±3.3m. Due to slope configuration, the course included a first portion of steep slope (on average 20°) with the first 9 gates, a flat transition of 7 gates (on average 11°) and a final medium steep portion of 5 gates before the time gate (on average 15°). Terrain tilted to skiers left direction on average by 4°.

The independent variable of the study was the position of the skier with respect to the ski binding: this factor was changed by acting on the relative position between the monoski suspension system and the foot sole component, as shown in Figure 1.d. Front (F), Mid (M) and Rear (R) adjustment were adopted: taking the most forward position as a zero reference, the F corresponded to -5mm, M at -20mm from F and R at -20mm from M. F was the usual setting adopted by the skier. The skier performed two runs for each of the three settings (i.e. F, M, and R). The three settings were blind tested by the skier. The runs were performed within a total time of 3 hrs, in a late march day with cloudy weather and air temperature ranging from -2°C to 4°C. After each run, subjective ratings regarding the skier's perception were collected. The course time, the skiing speed, the GRF signals, and the damper stroke signals were the dependent variables of the study.

During data analysis, GRF data were filtered at 2 Hz (4th order Butterworth low-pass filter), to exclude the disturbance from the snow surface high vibrational input, thus allowing a precise recognition of the skiing loads coming from turning dynamics. Conversely, the damper stroke signal was filtered at 25 Hz (4th order Butterworth low-pass filter) to maintain the significant peaks of stroke due to snow bumps or roughness. Kinetic data coming from the dynamometric platform were normalized to TW.

Data analysis was referred to the second run of each foot setting since the first run was used to allow the skier familiarizing with the course.

Three left turns and three right turns within both the steep and the medium course portion were analyzed for each run: the mean peak GRF values were averaged among the left and the right turns, separately. The highest peak over the entire course, named Grand peak, was also recorded.

Subjective ratings were collected as a score ranging from 0 to 5 in answer to questions on the perceived quality of the forward and upward position of the center of mass, the dynamic and quality of the suspension and the overall impression of foot setting and run performance (see supplementary materials for more details).

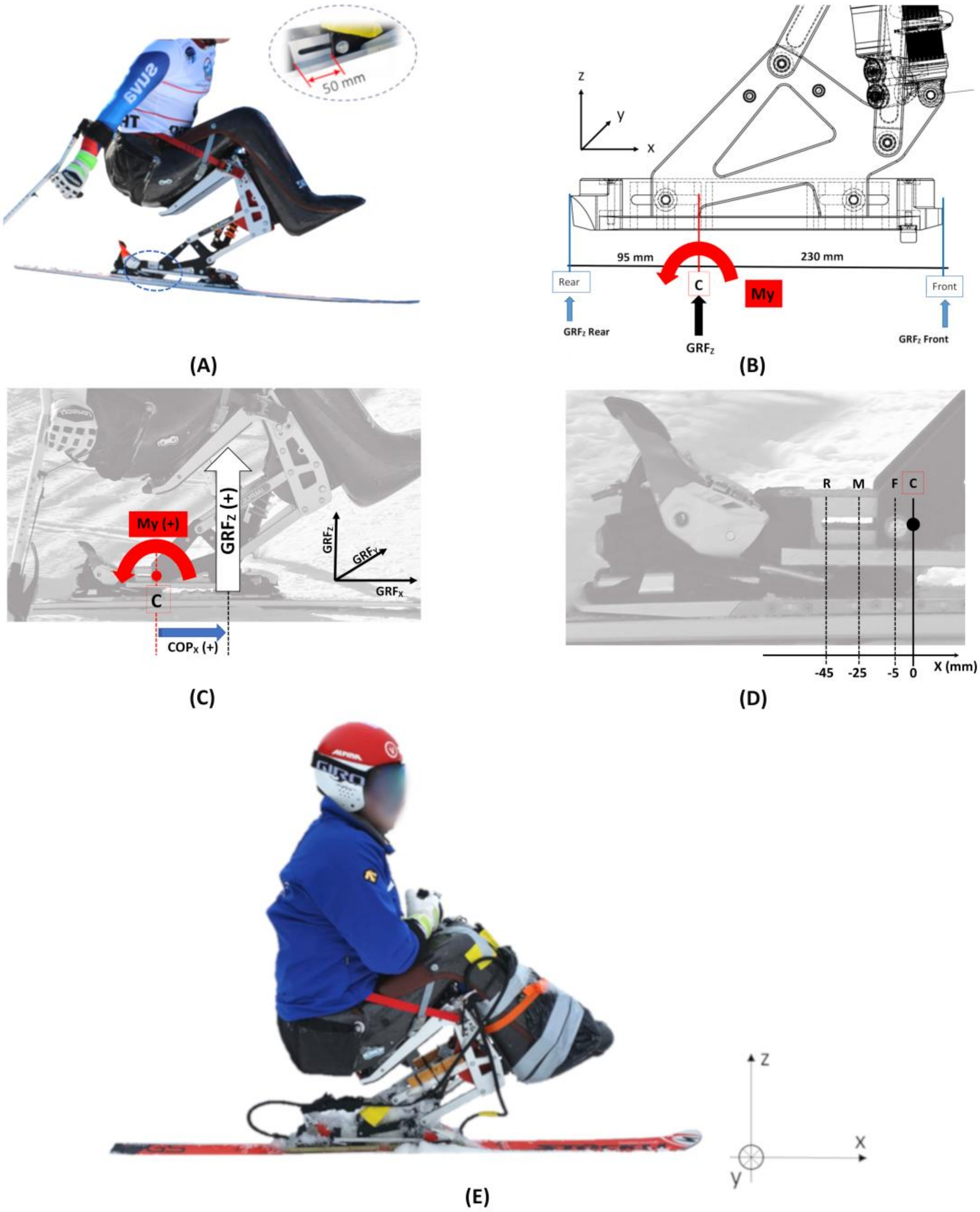

Figure 1. The monoski Impulse Boost by Unicent GmbH adopted for the study. (a) Detail of the 50mm adjustable range of the clamp; (b) Scheme of GRFz Front and Rear at the binding toe and at heel position, for foot setting M, giving the total GRF_Z normal to the foot sole and the total pitch moment M_Y; (c) Scheme of instantaneous longitudinal position of COPx for foot setting F; (d) Settings of suspension clamp to the foot, with respect to reference point C; (e) Overall view of the athlete equipped for the data collection during the giant slalom runs, with details of the dynamometric plate and of the stroke sensor.

4. Results

Loads measured in the steep portion are presented in Figure 2.a. GRF_Z and M_X are expressed respectively in N/TW and N·mm/TW. Right and left turns are identified by the zerocrossing of the roll moment signal M_X showing a zero value at the ski edge change. Given the reference system, a left turn corresponds to a positive ground reaction moment M_X applied by the snow to the dynamometric binding, that reverses during a right turn. GRF_Z shows a characteristic periodic pattern, with multiple peaks within each turn: the peak value of each turn is marked by a cross. The mean values of peaks of left and right turns are reported as dotted lines in Figure 2.a and are shown for left and right turns in Figure 2.c. The numerical results of the second run of each setting are reported in Table 1.

GRF_Z Grand peak value up to 3.36 times the TW was found with F setting. As an evidence, the peak loads in the left turns resulted consistently higher than the peak loads in the right turns. The ratio between left and right mean peak loads (L/R) was calculated and presented in Table 1 and Figure 2.d, for both the steep and the medium portion of the course. The L/R resulted consistently higher in the steep slope with increasing values when the foot setting moved from R to F.

The plot of GRF_Z with respect to its COP_x for the left and right turns recorded during setting F in the steep portion of the course is shown in Figure 2.b. Curves represent the pitching technique adopted by the skier in terms of magnitude of the GRF_Z and of COPx location along the ski. Three markers identify the beginning of the turn (green circle), the temporal midpoint of the turn (yellow triangle) and the end of the turn (red circle). This graph highlights the different pattern exerted by the skier during left and right turns, concerning the timing of the peak load that occurs typically at the midpoint of a right turn and much earlier during a left turn. If the COPx is averaged over the 6 turns of the steep course portion, its mean value can be expressed as a coordinate in the longitudinal X axis for both the steep and medium slope turns (Table 1). Interestingly, when compared to the three nominal settings (i.e. R, Mand F), the mean position of COPx proportionally increased when the foot nominal setting moved forward.

The analysis of damper speed peak values is reported in Figure 2.f. The highest compression speed was recorded for the R setting while the highest extension speed for the F setting.

The fastest run, the highest peak loads and the best subjective ratings were consistently obtained with the most forward setting (F).

Figure 2

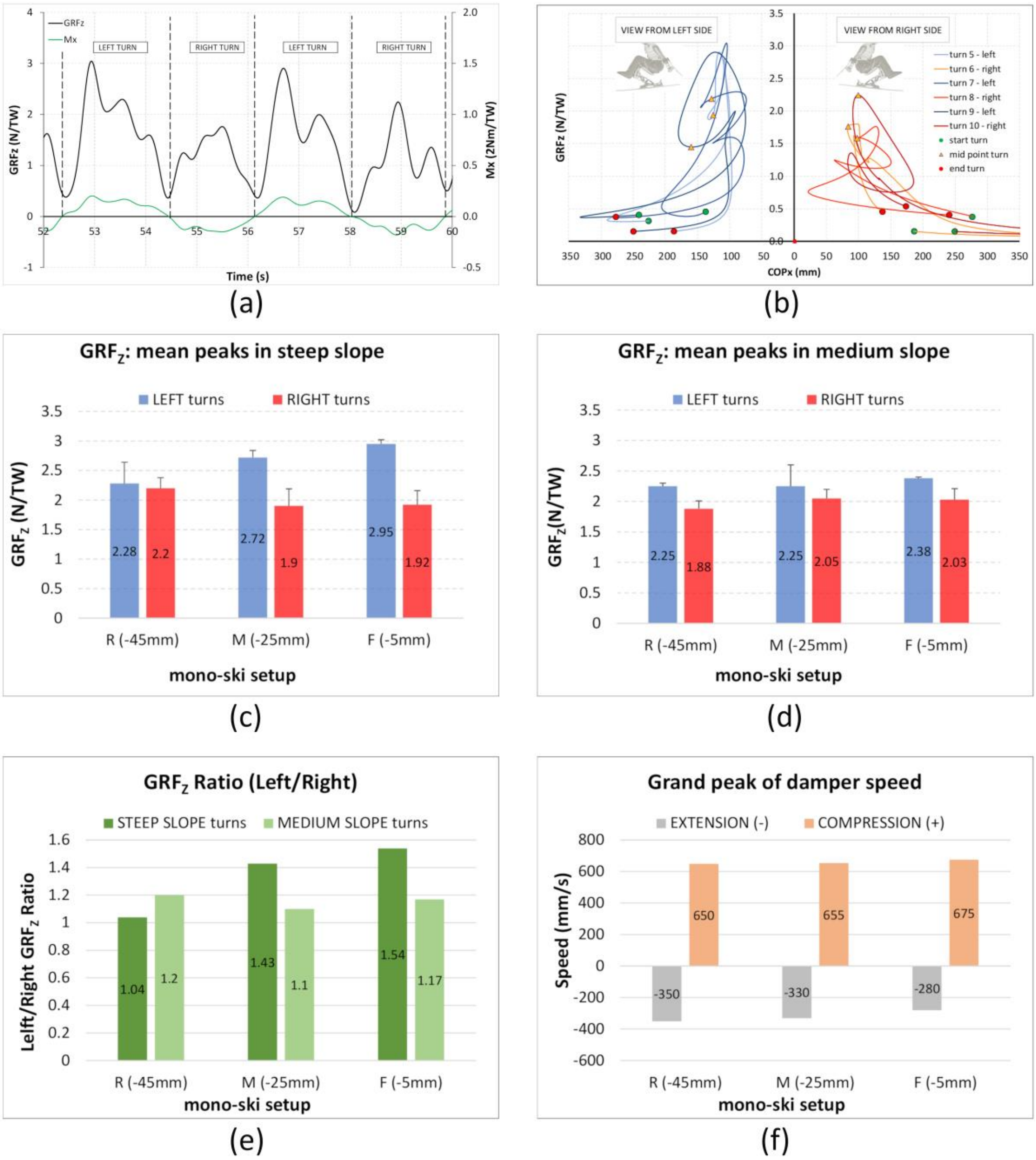

Figure 2. Results of the tests. (a) Loads measured in four slalom turns within the first 10 gates in the steep slope portion; (b) GRF_Z and COPx plots for Left and Right Turns with the characteristics events of each turn; (c,d) Mean peak values for the left and right turns at the different foot settings in the steep (c) and medium (d) slope; (e) Ratio between Left and Right mean peak GRF_Z loads at the different foot settings in the steep and medium slope; (f) Damper speed absolute peak values of compression and extension speed for the three foot settings.

Table1. Results from the second run performed for each foot setting. Data are presented as mean±standard deviation

		MEAN PEAKS OF GRFz				MEAN COPx				
MONO-SKI SETUP	Turns	Steep slope (N/TW)	Ratio (L/R)	Medium slope (N/TW)	Ratio (L/R)	Steep slope (mm)	Medium slope (mm)	Lap time (s)	Average speed (km/h)	Subjective rating (0-5)
F (-5mm)	Left	2.95±0.07	1.54	2.38±0.02	1.17	131	125	41.153	47.00	3.25
	Right	1.92±0.24		2.03±0.18						
M (-25mm)	Left	2.72±0.12	1.43	2.25±0.35	1.10	95	89	41.192	43.00	3.00
	Right	1.90±0.29		2.05±0.15						
R (-45mm)	Left	2.28±0.36	1.04	2.25±0.05	1.20	64	51	43.154	42.00	2.17
	Right	2.20±0.18		1.88±0.13						

5. Discussion

The study aimed to investigate the effect of monoski foot adjustment on kinematic and kinetic skiing parameters. The measurement system enabled analyzing GRFs applied to the binding of an elite Paralympic sit skier when repeating a giant slalom course with settings ranging from Front, Mid and Rear position of the suspension-foot assembly, with adjustment interventions of 20 mm.

The collected GRF_Z signals reached values that are considerably larger than those collected on a single leg during recreational carving skiing[20,21] and giant slalom skiing[11,12]. However, they are comparable with the sum of inner and outer skis. This is probably due because the monoski is the only interface between the skier and the snow and its trajectory is approximately the mid trajectory that a pair of skis may trace on the snow. The periodic nature of M_Y and M_X also corresponded to previous findings from dynamometric bindings[10,20].

The comparison between mean peak loads during left and right turns (Figures 2.c and 2.d) highlights that the skier coordination and balance control resulted asymmetric from a motor control perspective. The asymmetric behavior is evident both in the steep and in the medium portion of the course and is enhanced by the F setting although it resulted associated to the best speed, the highest loads and the best subjective rating. The small slope tilt of 4° towards the left was not considered to justify such large differences in GRFs when turning to the right, despite the possible banking effect. Therefore, higher loads during left turns could be charged mainly to technical skiing asymmetries. Anyway, the large increase of the L/R ratio on the steep slope with the forward frame settings deserves further investigations. This outcome regarding skiing kinetic asymmetry was very new to the skier and his coach so that they considered starting a specific training for balancing the turning technique.

The periodic pitching action of the skier was expressed by the forward-backward oscillation of the COPx (Figure 2.b). This cyclic shift of loads is consistent with other researches in the field of abled-bodied skiing[15,20] and corresponds to ski instructors recommendations to load the front shovel of the ski when entering the turn and to release it after the pole before changing the skiing side. Again, these actions were performed without symmetry by the elite skier involved in the present study. Indeed, peak loads during left turns were reached quite before the temporal midpoint of the turn (marked by triangles in Figure 2.b), whereas the peak loads occurred at the midpoint during right turns. Differences between the longitudinal location of the COM projection along the ski between abled-bodied and sit-skiers shall be taken into account, as in neutral skiing position the typical boot location along the ski that is valid for abled-bodied skiers may need a different adjustment for sit-skiers.

An interesting finding that deserves attention is the relationship between the foot setting and the mean longitudinal COPx location : adjustments of 20 mm on the foot-suspension assembly induced translations that were 1.765 times larger of the COPx mean location along the ski. This finding is in line with those of similar studies[8] and can be justified considering the tridimensional nature of skiing trajectory, that implies also the height of the center of mass (COM) of the sit skier and the need of producing the GRF as the resultant of a pressure distribution developed along the ski length[22,23].

The results of damper speed analysis can be of interest for the monoski designer contributing to the choice of dampers with the more appropriate force-speed characteristics. Even though the damper setting was not modified during the tests, the adopted method gave quantitative confirmation to the sit skier's evaluations of damper rebound changes from R to F setting. Indeed, a reduction of about 25% was measured in the rebound speed from foot setting R to F.

From a methodological point of view, the work has some limitations worthy to be mentioned.

First, we presented a single subject study on a world-class elite skier and thus results could not be applied to large populations of sit-skiers. Sit skiers competing at such level in the giant slalom discipline with the same spinal cord lesion and classification are usually from different international countries and typically meet only for a world championship or Olympic games. In any case, given classification differences among the skiers, their time course is modified by a set of penalty factors that are under discussion within the IPC and the scientific community[24].

Second, the number of runs repeated by the skier was limited to two. This may be considered a limitation from the reliability point of view also considering that the skier had a short adaptation time to familiarize himself with the setting. Nevertheless, the effect of possible changes in the snow conditions during the day of testing and the possible damage to the snow surface at each gate were assumed to be predominant. Indeed, the total number of 6 runs was adopted to limit the temperature and snow changes, ensuring a constant condition of the ski slalom course. It shall be mentioned also that values supporting the F setting may result from the fact that it was the usual setting adopted by the skier. Finally, the small range of foot adjustment (40 mm) explored in the present study did not allow finding an absolute optimal foot setting, thus giving only indications about the direction of improvement. Larger ranges of adjustment, as in an analog work[8], were not explored to avoid modifications to the monoski structure or the application of additional mechanical components.

6. Conclusions

The change of foot setting from R to M (+20mm) and F (+40mm) resulted to have a positive influence in the performance of the giant slalom world-class sit skier measured: time lap was reduced and average speed and subjective rating increased with the F setting. Correspondingly, the mean peak values of GRFz increased up to 2,95 times TW. The method developed allowed to highlight an asymmetric behavior between right and left turning, with GRF_Z in left turns being up to 54% larger than right turns. These results could be useful for skiers and trainers to improve the skiing technique. Moreover, the magnitude of the loads together with the measured damper speed could be useful for the design process of optimized monoski for a wider dissemination of Paralympic alpine sit skiing.

7. Practical Implications

Dynamic values of GRFs collected during professional elite skiing in giant slalom events could support the engineering design of safe racing equipment, the development of safety standard tests for such expensive devices and the design of optimized monoski oriented to enhance performance and/or reduce cost.

The method allowed quantifying a skiing asymmetry of the skier between left and right turns that was unknown, inducing the coach and the skier to plan interventions for balancing the two sides: this could lead to further overall performance improvement.

The evidence to the presence of an optimal foot setting, as confirmed by subjective and objective evaluations, shall guide monoski designers and users to consider wider options of foot adjustment aiming to increase skiing performance and safety.

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

REFERENCES

1. Goll M, Wiedemann MSF, Spitzenpfeil P. Metabolic demand of paralympic alpine skiing in sit-skiing athletes. *J Sport Sci Med*. 2015.

2. *Epidemiology of Injury in Olympic Sports*.; 2009. doi:10.1002/9781444316872.
3. McBeth PB, Ball CG, Mulloy RH, et al. Alpine ski and snowboarding traumatic injuries: incidence, injury patterns, and risk factors for 10 years. *Am J Surg*. 2009. doi:10.1016/j.amjsurg.2008.12.016.
4. Derman W, Schwellnus MP, Jordaan E, et al. High incidence of injury at the Sochi 2014 Winter Paralympic Games: A prospective cohort study of 6564 athlete days. *Br J Sports Med*. 2016. doi:10.1136/bjsports-2016-096214.
5. Derman W, Blauwet C, Webborn N, et al. Mitigating risk of injury in alpine skiing in the Pyeongchang 2018 Paralympic Winter Games: The time is now! *Br J Sports Med*. 2018. doi:10.1136/bjsports-2017-098864.
6. Technological developments for people with a disability — removing barriers to participation and enhancing sports performance. *J Sci Med Sport*. 2003. doi:10.1016/s1440-2440(03)80163-9.
7. Oh H, Johnson W, Syrop IP. Winter adaptive sports participation, injuries, and equipment. *Sports Med Arthrosc*. 2019. doi:10.1097/JSA.0000000000000236.
8. Langelier E, Martel S, Millot A, et al. A sit-ski design aimed at controlling centre of mass and inertia. *J Sports Sci*. 2013. doi:10.1080/02640414.2012.762598.
9. ANSI/RESNA. *No Title ASE-1:2016 Adaptive Sports Equipment: Volume 1: Winter Sports Equipment*.; 2016.
10. Kersting UG, Kurpiers N, Hild E, et al. Comparison of a six degree-of-freedom force sensor and pressure insole measurements in selected skiing manoeuvres. *Clin Biomech*. 2011.
11. Müller E, Schwameder H. Biomechanical aspects of new techniques in alpine skiing and ski-jumping. In: *Journal of Sports Sciences*.; 2003. doi:10.1080/0264041031000140284.
12. Spörri J, Kröll J, Schwameder H, et al. Course setting and selected biomechanical variables related to injury risk in alpine ski racing: An explorative case study. *Br J Sports Med*. 2012. doi:10.1136/bjsports-2012-091425.
13. Gilgien M, Spörri J, Chardonnens J, et al. Determination of the centre of mass kinematics in alpine skiing using differential global navigation satellite systems. *J Sports Sci*. 2015. doi:10.1080/02640414.2014.977934.
14. Fasel B, Spörri J, Gilgien M, et al. Three-dimensional body and centre of mass kinematics in alpine ski racing using differential GNSS and inertial sensors. *Remote Sens*. 2016. doi:10.3390/rs8080671.
15. Kröll J, Spörri J, Gilgien M, et al. Sidecut radius and kinetic energy: Equipment designed to reduce risk of severe traumatic knee injuries in alpine giant slalom ski racing. *Br J Sports Med*. 2016. doi:10.1136/bjsports-2015-095463.
16. Supej M, Senner V, Petrone N, et al. Reducing the risks for traumatic and overuse injury among competitive alpine skiers. *Br J Sports Med*. 2017;51(1). doi:10.1136/bjsports-2016-096502.
17. Petrone N, Marcolin G, Cognolato M, et al. The effect of buckle closure and temperature on the in-vivo flexibility of ski-boots: A pilot study. In: *Procedia Engineering*.Vol 72.; 2014. doi:10.1016/j.proeng.2014.06.108.
18. Gilgien M, Spörri J, Limpach P, et al. The effect of different global navigation satellite system methods on positioning accuracy in elite alpine skiing. *Sensors (Switzerland)*. 2014. doi:10.3390/s141018433.

19. Gilgien M, Crivelli P, Spörri J, et al. Characterization of course and terrain and their effect on skier speed in World Cup alpine ski racing. *PLoS One*. 2015. doi:10.1371/journal.pone.0118119.
20. Federolf P, Roos M, Lüthi A, et al. Finite element simulation of the ski-snow interaction of an alpine ski in a carved turn. *Sport Eng*. 2010. doi:10.1007/s12283-010-0038-z.
21. Panizzolo FA, Marcolin G, Petrone N. Comparative evaluation of two skiing simulators as functional training devices for recreational skiers. *J Sport Sci Med*. 2013;12(1).
22. Scott N, Yoneyama T, Kagawa H, et al. Measurement of ski snow-pressure profiles. *Sport Eng*. 2007. doi:10.1007/bf02844186.
23. Petrone N. The use of an Edge Load Profile static bench for the qualification of alpine skis. In: *Procedia Engineering*.Vol 34.; 2012. doi:10.1016/j.proeng.2012.04.066.
24. Tweedy SM, Vanlandewijck YC. International Paralympic Committee position stand--background and scientific principles of classification in Paralympic sport. *Br J Sports Med*. 2011;45(4):259-269. doi:10.1136/bjsm.2009.065060.

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