THE EFFECT OF TOUCHDOWN KINEMATICS ON FORWARD ACCELERATION IN THE SKELETON PUSH START

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Producing forward acceleration in a bent-over position while pushing a sled is poorly understood. Therefore, the purpose of this study was to investigate body and segment orientation of 16 elite skeleton athletes for the ground contacts 1 to 3 after the start and after 15 m as well as to quantify their relation to forward acceleration. Kinematic and kinetic data were recorded indoor on an athletics track whilst the athletes were pushing a sled dummy along guiding rails. Trunk and thigh orientation remained similar during the acceleration phase, while changes in touchdown kinematics originated from the shank and foot segment. Variance in forward acceleration could be sig. explained by shank orientation (R^2_{adj} = 0.84). Consequently, training interventions to modify shank orientation in skeleton should be developed.

KEYWORDS: performance enhancement, winter sports, athletic sprinting, bobsleigh.

INTRODUCTION: In the Winter Olympic sliding sport skeleton, athletes start a run by sprinting with maximal effort whilst pushing their sled in a bent-over posture for 20-30 m before loading the sled to slide down an ice track (Colyer et al., 2017). As in bobsleigh, start time and terminal velocity of the push phase are considered major contributors to final race time (Zanoletti et al., 2006). While favourable anthropometric and physical abilities of good accelerators in the skeleton push phase have been identified (Sands et al., 2005; Colyer et al., 2017), kinematic and kinetic performance characteristics whilst pushing a sled in a bent-over posture are poorly understood. Besides step characteristics (Needham et al., 2021) authors have focused on foot placement strategies as well as trunk orientation and knee angles during the start position and the following ground contacts (Kivi et al., 2004; Oguchi et al., 2021). Gong et al. (2021) found evidence that the position of the foot relative to the body centre of mass (CoM) at initial ground contact – touchdown angle or angle of attack (AoA) – might be linked to performance, which is in line with studies focusing on athletic sprinting (Kugler et al., 2010). Besides the posture of the whole body, there exists evidence from studies on both sprinting (King et al., 2023) and bobsleigh (Zedler et al., 2023 in preparation) that forward orientation of the thigh, shank and foot at touchdown are important features of good accelerators. However, it remains unclear to which extent these findings can be translated to the push start in skeleton. Due to the high task constraint imposed by the flexed posture in skeleton, it is reasonable to assume that athletes are limited in their ability to change the orientation of their lower limb segments at touchdown as distance and velocity increase. Therefore, the aim of this study was to investigate the touchdown kinematics (body posture and segment orientation) in the skeleton push start for the initial acceleration phase (contacts 1-3 after the start) and the ground contacts after 15 m, as well as to quantify their relationship to forward acceleration about the stance phase as a measure of performance.

METHODS: Based on ongoing performance diagnostics with the German national skeleton team, sixteen elite skeleton athletes (8 male: 23.8 years, 1.79 m, 79.1 kg; 8 female: 23.5 years, 1.72 m, 67.5 kg) performed push starts on a level indoor athletics track while pushing a sled dummy along guiding rails which were mounted on the track. The kinematics of athlete and the sled as well as the ground reaction forces of the first three ground contacts after the start and the ground contacts after 15 m were analysed. Therefore, the positional data of retro-reflective markers (Ø 14 mm) attached to both athlete (54 markers) and sled (4 markers) were recorded by 16 infrared cameras (250 Hz, Fx40, Vicon, Oxford, UK), while ground reaction forces (GRF) were simultaneously sampled by three force plates (1250 Hz, 600 x 900mm, Kistler, Winterthur, CH) embedded into the ground. Both kinematic and kinetic data were filtered recursively using a low-pass 4th order Butterworth filter (cut off frequency: 25 Hz). Touchdown kinematics (Table 1) were defined as the angle of attack and the orientation of trunk, thigh, shank and foot angle at initial ground contact (resultant GRF exceeding a threshold of 20 N). For all segments smaller angles resemble orientations more towards the running direction.

Table 1: Definition of sampled variables summarised as touchdown kinematics.

Variable	Definition
Angle of attack [°]	Angle between the ground and the vector pointing from centre of force application on the force plate to the body CoM (De Leva, 1996).
Trunk angle [°]	Angle between the ground and the vector pointing from the midpoint of the pelvis to the midpoint of the upper trunk.
Thigh angle [°]	Angle between the ground and the vector pointing from lateral knee epicondyle to greater trochanter.
Shank angle [°]	Angle between the ground and the vector pointing from lateral malleolus to lateral knee epicondyle.
Foot angle [°]	Angle between the ground and the vector pointing from fifth metatarsophalangeal joint to calcaneus.

As a measure of performance of a ground contact of interest, the average horizontal acceleration of both athlete and sled (AHAC) was calculated based on the antero-posterior GRF as recommended by Zedler et al. (2023). Therefore, the force was numerically integrated with respect to time and further divided by the mass of athlete and sled (30 kg) and by ground contact time. The change in body and segment orientation throughout the push phase was investigated using a one way repeated-measures ANOVA ($\alpha = 0.05$) with push distance as factor (ground contacts C1-C3 after the start and after 15 m for inside (15in) and outside leg (15out). The inside leg is defined as the leg closer to the sled. Due to the starting pose of the athletes, TD of C1 was inside. To quantify the relation between TD kinematics and performance, a stepwise multiple linear regression model was fitted to all ground contacts (n = 80) using angle of attack and trunk, thigh, shank and foot angle as predictors and AHAC as response variable. Calculations were done using Matlab's stepwiselm function (R2023a, The Mathworks Inc., Natick, Massachusetts, US). This algorithm uses forward and backward regression to add or remove predictors starting from a constant model based on a criterion (increase in $R^2_{adj} > 0.05$).

RESULTS: Average trunk and thigh angles at TD remained similar for the first 15 m of the phase, while there was a sig. main effect of push distance ($p < 0.001$) for angle of attack, shank and foot angles (Table 2).

Table 2: Touchdown kinematics for the ground contacts C1-C3 and after 15 m. Sig. main effects (p < 0.001) were found for angle of attack (AoA), shank and foot angles. Sig. differences for multiple comparisons between ground contacts are marked as follows (a = diff. to C1, b = diff. to C2, c = diff. to C3, d = diff. to 15out, e = diff. to 15in).

Contact	AoA [°]	Trunk [°]	Thigh [°]	Shank [°]	Foot [°]
C1	$81.6 \pm 4.3^{b,d,e}$	2.7 ± 2.7	124.8 ± 4.6	$39.3 \pm 5.1^{b,c,d,e}$	$140.8 \pm 7.5^{b,c,d,e}$
C2	$86.7 \pm 4.8^{a,d,e}$	3.8 ± 3.3	125.4 ± 4.9	$51.8 \pm 5.3^{a,d,e}$	$153.4 \pm 7.5^{a,c,d,e}$
C3	$83.1 \pm 5.2^{d,e}$	4.1 ± 3.3	125.5 ± 6.0	$50.9 \pm 7.4^{a,d,e}$	$148.3 \pm 6.7^{a,b,d,e}$
15out	$99.7 \pm 3.4^{a,b,c}$	5.3 ± 3.0	124.9 ± 3.9	$77.7 \pm 4.2^{a,b,c}$	$166.2 \pm 5.5^{a,b,c}$
15in	$99.4 \pm 4.8^{a,b,c}$	5.0 ± 2.9	128.6 ± 3.3	$73.5 \pm 7.8^{a,b,c}$	$162.2 \pm 5.2^{a,b,c}$

AHAC for the initial acceleration amounted to 3.73 ± 0.60 (C1), 3.17 ± 0.45 (C2), 2.76 ± 0.50 (C3) and to 1.54 ± 0.33 (15out) and 1.33 ± 0.37 (15in). The linear model sig. ($p < 0.001$) explained the variance in AHAC using only shank angle at TD as predictor ($R^2_{adj} = 0.84$).

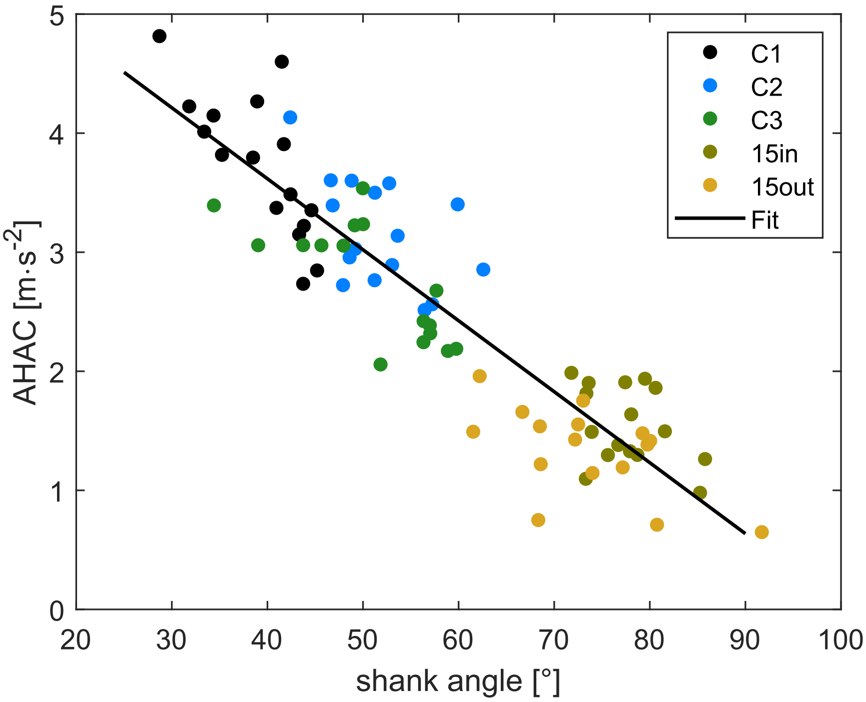

Figure 1: Scatter plot of shank angle at TD and average horizontal acceleration of athlete and sled (AHAC) for the ground contacts C1-3 and after 15 m for both inside (15in) and outside leg (15out). The solid line represents the fitted linear model to the data explaining 84 % of variance in acceleration (AHAC = 6 – 0.06 shank angle). Smaller angles represent orientations more towards the running direction.

DISCUSSION: The aim of this analysis was to investigate TD kinematics of the push phase in skeleton and to quantify its impact on forward acceleration. The angles of attack for C1-3 in this study were in close agreement with values published by Gong et al. (2021). During the initial acceleration phase the athletes were able to place their foot behind the CoM, while after 15 m the foot was placed slightly in front of the CoM on average (angle of attack > 90°) which is likely to result in braking forces during the subsequent ground contact. Since the angle of attack can be interpreted as a variable which quantifies the position of the whole body in relation to the centre of force application on the ground, it is worthy to elaborate the orientation of the individual segments in space. It was assumed that the bent-over posture imposes a task constraint on the athletes which limits their ability to position their body segments in space. The results of this work support this assumption, since the trunk and thigh angle at TD did only marginally change over the course of 15 m. The trunk remains close to being parallel to the ground and the thighs are oriented posteriorly with the knee being located in front of the greater trochanter. Both trunk and thigh orientation in the skeleton push phase contrast the knowledge on the acceleration phase in athletic sprinting where athletes progressively erect their body to an upright posture as velocity increases (Donaldson et al., 2020). Since trunk and thigh orientation in skeleton remain unaffected as velocity increases, changes in TD kinematics must be induced from changes in shank and foot orientation. Both shank and foot orientation during the initial steps (C1-3) are significantly smaller compared to 15 m (inside and outside leg), which supports this line of reasoning. The shank segments of skeleton athletes in this study were tilted more towards horizontal for C1-3 compared to elite sprinters (Donaldson et al., 2020), which might be realised by supporting their upper body on the sled. It is noteworthy that despite the fact that trunk and thigh orientation did not sig. change from C1 to 15 m, interindividual differences were present. This suggests individual TD strategies which are maintained throughout the push phase. To quantify the effect of TD kinematics on forward acceleration a stepwise multiple linear regression model was fitted to all ground contacts. The model was able to explain variance in AHAC by 84 % solely based on shank angle. This finding is in line the concept of 'posture before power' (Alt et al., 2022), which stresses the importance of shank orientation to effectively create anteriorly directed GRF. Moreover, both King et al. (2023) and Zedler et al. (2023, in preparation) have found relationships between foot and shank orientation and propulsion for athletic sprinting and the push phase in bobsleigh. However, the importance of foot orientation could not be confirmed for skeleton. Asymmetries between the inside and outside leg as pointed out by Needham et al. (2021) regarding step characteristics were not found regarding TD kinematics. Even if there were asymmetries during the first steps (C1-3), they would be difficult to interpret, because the forward velocity of the athlete changes from step to step. At 15 m the velocity of the athlete was close to their individual top speed resulting in low acceleration. Although there were no statistically sig. differences in TD kinematics between inside and outside leg, AHAC was lower during ground contacts of the inside leg. Since AHAC resembles the forward acceleration normalised to stance time, this difference might also be due to shorter ground contact times for the outside leg. To draw conclusions regarding the propulsive contribution of inside and outside leg, AHAC might be unsuitable and therefore further research is necessary.

CONCLUSION: In the skeleton push start, changes in TD kinematics are realised by changes in shank and foot orientation while the trunk and thigh angles remain unaffected regardless of velocity. Especially the shank orientation seems to be an important contributor to propulsion. Therefore, training interventions to modify shank orientation at TD should be developed.

REFERENCES

Alt, T., Oeppert, T. J., Zedler, M., Goldmann, J.-P., Braunstein, B., & Willwacher, S. (2022). A novel guideline for the analysis of linear acceleration mechanics - outlining a conceptual framework of 'shin roll' motion. *Sports biomechanics*, 1–18.

Colyer, S. L., Stokes, K. A., Bilzon, J. L. J., & Salo, A. I. T. (2017). Skeleton sled velocity profiles: a novel approach to understand critical aspects of the elite athletes' start phases. *Sports Biomechanics*, 17(2), 168–179.

Donaldson, B. J., Bayne, H., & Bezodis, N. E. (2020). A comparison of trunk and shank angles between elite and sub elite sprinters during sprint acceleration. *Proceedings of the 38th International Society of Biomechanics in Sport Conference*, Online activities: July 20-24.

Gong, M., Gao, C., Tian, G., & Gao, B. (2021). Kinematic determinants of acceleration in skeleton push phase. *International Journal of Performance Analysis in Sport*, 21(6), 1004–1014. doi: 10.1080/24748668.2021.1968661

Needham L, Evans M, Cosker DP, Colyer SL (2021). Development, evaluation and application of a novel markerless motion analysis system to understand push-start technique in elite skeleton athletes. *PLoS ONE* 16(11): e0259624. doi: 10.1371/journal.pone.0259624

Oguchi, T., Ae, M., & Schwameder, H. (2021). Step characteristics of international-level skeleton athletes in the starting phase of official races. *Sports biomechanics*, 1–14.

King, D., Burnie, L., Nagahara, R., & Bezodis, N. E. (2023). Relationships between kinematic characteristics and ratio of forces during initial sprint acceleration. *Journal of sports sciences*, 1–9.

Kivi, D., Smith, S., Duckham, R., & Holmgren, B. (2004). Kinematic analysis of the skeleton start. ISBS 2004: Proceedings of the Biomechanics in Sports 2004 international symposium, 450–452, from https://dro.deakin.edu.au/view/du:30067029.

Kugler, F., & Janshen, L. (2010). Body position determines propulsive forces in accelerated running. *Journal of biomechanics*, 43(2), 343–348.

Sands, W. A., Smith, L. S. L., Kivi, D. M. R., McNeal, J. R., Dorman, J. C., Stone, M. H., & Cormie, P. (2005). Anthropometric and physical abilities profiles: US National Skeleton Team. *Sports biomechanics*, 4(2), 197–214.

Zanoletti, C., La Torre, A., Merati, G., Rampinini, E., & Impelizzeri, F. M. (2006). Relationship between push phase and final race time in skeleton performance. *Journal of strength and conditioning research*, 20(3), 579–583.

Zedler, M., Alt, T., Potthast, W., Braunstein, B., Goldmann, JP (2023). Evaluating performance measures for the bobsleigh push start. *Proceedings of 41st International Society of Biomechanics in Sports Conference*, Milwaukee, USA: July 12-16, 2023.