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HIP AND SHOULDER KINEMATICS DURING INITIAL SLED ACCELERATION IN LUGING – A CASE STUDY

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ABSTRACT
Purpose. The start is treated as one of the most important technical elements in all sliding sports, as it is the only phase when athletes can actively contribute to increasing sled velocity. Nevertheless, start kinematics in luging have seldom been addressed in literature. Therefore, the aim of this study was to analyse hip and shoulder movement of lugers during one of the essential start phases – the pull and push-off from the start handles – to further understanding of the velocity development process at its initial stage. **Methods.** Three experienced female lugers volunteered to take part in the case study. A number of start attempts were filmed and analysed using a motion tracking method. **Results.** The study found that an athlete and the sled do not move as a whole rigid system, and a hip movement relative to the sled was found to exist. The study participants used two techniques for achieving high sled velocity: by initially pulling on the start handles with a powerful back extension, and sliding the hips forward on the sled in an attempt to increase forward momentum; a combination of both techniques might provide increased performance. Athletes featured two weaknesses in terms of where horizontal sled velocity was lost – at the end of the initial pull on the handles and during the final moment of the push-off from the handles. The latter was previously believed to be another option at gaining increased sled horizontal velocity. **Conclusions.** As found in the results, athletes have at least two possibilities of increasing horizontal sled velocity. Hip movement relative to the sled appeared to be important for gains in velocity. Additional studies that analyse larger pulls are necessary for understanding the role of hip and sled relative movement in start technique and its impact on increasing initial velocity.

Key words: biomechanics of winter sports, in-run performance, motion analysis, start technique

Introduction

The sport of luge is one of the fastest winter Olympic sports. According to the rules of the International Luge Federation [1], race times are recorded with accuracy up to 0.001 of a second and it is not uncommon that just several thousandths of a second determine the winner of a race.

There are four split times that are assessed in competitive luge: the start time and three interval times. The start is considered to be the most important technical element in luge [2], and start records are officially registered during major competitions. It has been proven in previous research that a fast start in luge, as well as in other sliding sports, is a necessary requirement for sporting success [3–6]. According to Kearney et al. [7], start performance on an indoor ramp is part of a battery of tests that candidates undergo when qualifying for the US National Luge Team.

Lugers put an intense focus on mastering start technique. Not only are luge tracks used for this purpose, but also start simulators and specially constructed start ramps that are both iced and designed for roller sleds. An iced start ramp for sliding sports simulates the start portion of the sliding track and allows lugers to practise start technique during the late off-season period, when temperatures are still too high to allow icing of the whole sliding track.

Despite the efforts by lugers in improving start technique, studies on start kinematics in luge are scarcely published; more attention is paid to equipment modifications and physical conditioning. One study that researched this issue was by Kempe and Thorhauer [8], who defined five phases during the start in luge: (1) pushing the sled forward whilst holding to the start handles; (2) sliding backwards with the sled, or the "compression" phase; (3) push-off from the start handles; (4) several paddling arm strokes; (5) and assuming a race position on the sled.

The first three phases occur almost exclusively on the horizontal start platform of the track or ramp; it is in the third phase when athletes begin to slide out from the horizontal to the sloped portion of the track. In this phase, athletes attempt to reach the highest possible sled velocity. In fact, the third phase does not consist of purely pushing-off from the handles, as athletes begin the start phase from behind the handles and first pull themselves and the sled up to the handles in order to be able to push-off (Fig. 1). Therefore, the aim of this study was to analyse the underlying kinematics of torso move-

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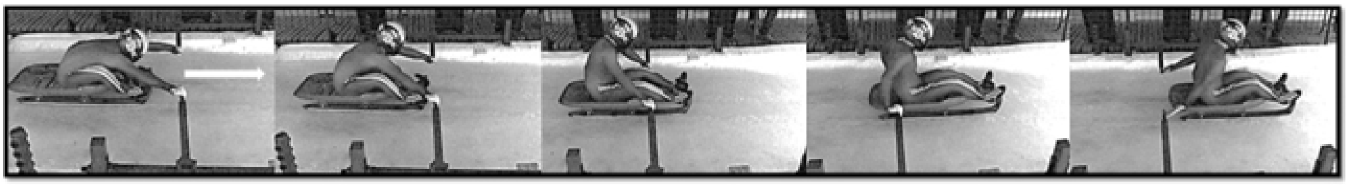


The first three images show an athlete pulling up to the start handles. Push-off is shown in the last two images

Figure 1. Third start phase in luge – push-off from the handles

ment during this push-off phase (Phase 3), and to determine the best technique that maximises sled velocity as well as understand the reasons for velocity losses.

Material and methods

Three female lugers (Tab. 1) with more than three years of international competitive experience provided their informed consent to take part in the study. The participants were told they would be filmed during their training session on an iced start ramp and have their start technique examined for later analysis. The training session was held during a training camp in the late pre-season period. Following a warm-up on an athletic field, each athlete performed several warm-up starts on the start ramp and then completed four maximum effort starts consisting of all five phases as previously described; the participants were provided with 2–3 minutes rest between each start attempt.

Video recording was performed with two Basler A602fc high-speed video cameras (Basler AG, Germany), filmed at 100 fps at a resolution of 656 × 490 pixels. One camera was located on the left hand side of the start platform, with the camera's optical axis perpendicular to the movement direction. The camera was set 2 m from the centre of the lane (as far as was possible due to the size of the ramp hall) and 1.5 m from the platform's edge. This provided a frame of reference that covered the entire start platform. The other camera was placed 3 m above the centre of the iced lane, 5 m from the beginning of the start platform, with the optical axis tilted 30° down as to provide a full view of the start platform and the first paddling arm stroke.

Prior to the training session, a 3D model of the start platform was created using the Simi Motion 3D calibration system for later motion analysis (SIMI Reality Motion Systems GmbH, Germany). At least 12 calibration points that could be simultaneously filmed by both cameras were used in accordance with the requirements of the Simi Motion 3D software package. Measurement points including two body markers (left hip and left shoulder) and one sled marker (at the centre of the frontal part of the pod) were manually digitized in each frame during the third phase of the start, with the hip's and sled's x (horizontal) coordinate and the shoulder's x and z (horizontal and vertical) coordinates considered for analysis. The beginning of the forward movement of the sled (beginning of Phase 3) and the instant when the luger pushed-off from the handles (end of Phase 3) were then determined, with the timing of each event derived from the video's frequency.

In total, the following parameters were considered for evaluation: the time to perform Phase 3; the horizontal position of the hip and shoulder; the vertical position of the shoulder; sled, hip and shoulder horizontal velocity (end velocity of the sled was measured exactly at push-off); and shoulder vertical velocity. Horizontal velocity was considered to have a positive value in the direction towards the slope of the ramp; a positive vertical velocity was treated as the direction upwards from the ice surface. The position of the start handles was used as a reference for measuring movement in both the horizontal and vertical direction. Velocity was determined as the first-order derivative of the corresponding coordinates using a built-in algorithm in the motion analysis software. Measurement accuracy was 0.02 m and 0.04 m $\cdot$ s^{-1} for velocity.

Table 1. Participants in the study

Participant	Age (years)	Height (m)	Body mass (kg)
A	37	1.74	86.6
B	25	1.73	73.1
C	19	1.70	69.1

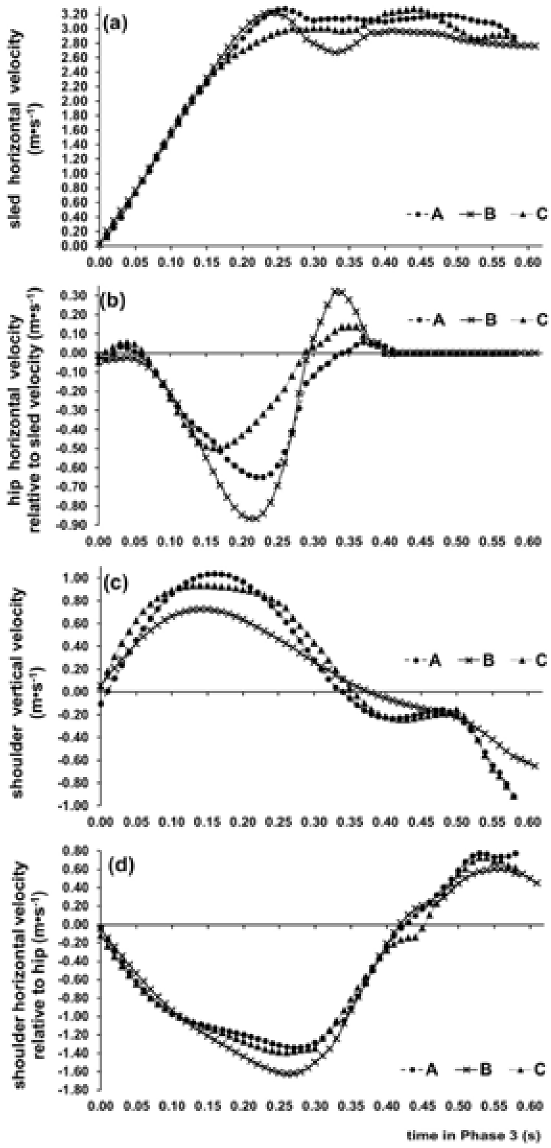
Results

Table 2 summarizes all Phase 3 velocity measurements averaged for each athlete over the four trials. It can be seen that athlete B showed lower horizontal sled velocities in comparison to the other two athletes, as well as also featuring the longest-lasting Phase 3. The sled velocities of athletes A and C did not differ substantially, though athlete C had slightly higher sled horizontal velocity at push-off. Athlete B was also slower in terms of vertical shoulder movements, but faster in hip movements relative to the sled as well as in backward shoulder movement, while positive horizontal shoulder movement (relative to the hip) was lower than for the other two athletes.

Figure 2 illustrates the velocity curves of the sled, hip and shoulder with respect to the duration of Phase 3; the curves have been averaged for each athlete's four start attempts. Differences in the sled velocity curves appear after 0.16 s from the beginning of the start phase.

Table 2. Average velocities of the four start attempts and Phase 3 duration (mean ± SD)

	Athlete		
	A	B	C
Duration of Phase 3 (s)	0.58 ± 0.01	0.61 ± 0.01	0.58 ± 0.01
End sled velocity (m · s^{-1})	2.81 ± 0.04	2.76 ± 0.05	2.86 ± 0.04
Maximum sled velocity (m · s^{-1})	3.29 ± 0.03	3.22 ± 0.06	3.28 ± 0.07
Average sled velocity (m · s^{-1})	2.39 ± 0.04	2.29 ± 0.04	2.40 ± 0.05
Drop in sled velocity from maximum to end velocity (m · s^{-1})	–0.48 ± 0.04	–0.46 ± 0.06	–0.42 ± 0.05
Maximal hip negative velocity relative to sled velocity (m · s^{-1})	–0.66 ± 0.04	–0.87 ± 0.05	–0.51 ± 0.05
Maximal hip positive velocity relative to sled velocity (m · s^{-1})	0.12 ± 0.01	0.37 ± 0.03	0.19 ± 0.02
Maximal shoulder negative horizontal velocity relative to hip velocity (m · s^{-1})	–1.35 ± 0.05	–1.65 ± 0.04	–1.42 ± 0.05
Maximal shoulder positive horizontal velocity relative to hip velocity (m · s^{-1})	0.89 ± 0.03	0.62 ± 0.02	0.78 ± 0.03
Maximal shoulder positive vertical velocity (m · s^{-1})	1.04 ± 0.05	0.73 ± 0.03	0.94 ± 0.05
Maximal shoulder negative vertical velocity (m · s^{-1})	–0.92 ± 0.05	–0.65 ± 0.05	–0.94 ± 0.04



(a) sled horizontal velocity
(b) hip horizontal velocity relative to the sled
(c) shoulder vertical velocity
(d) shoulder horizontal velocity relative to the hip

Figure 2. Average velocities with respect to Phase 3 duration

Athletes A and B continued to feature a rapid rise in sled velocity until reaching their maximum velocity. On the other hand, Athlete C plateaued in sled velocity, and the maximum was reached only towards the end of the phase (Fig. 2a).

Differences in shoulder velocities can be observed at the beginning of Phase 3; athletes A and C featured a steeper initial portion of both shoulder velocity curves than athlete B (Fig. 2c and d). Hip velocity curves relative to sled velocity showed a shift in the minimum peak with respect to each other. For athletes A and B, this peak occurred shortly before maximum sled velocity; for athlete C, hip relative velocity minimum did not have a timing relationship with the maximum sled velocity (Fig. 2b).

Table 3 presents the mean joint kinematics of the hip and shoulders, averaged over the four attempts. These data show that athletes A and C had the same initial and final hip position. Athlete B's hip position at the beginning of pulling phase to the start handles was closer, and farther at the instant of pull-off from the start handles, than of the other two athletes. As a result, total hip displacement during this examined start phase was very similar among all three athletes.

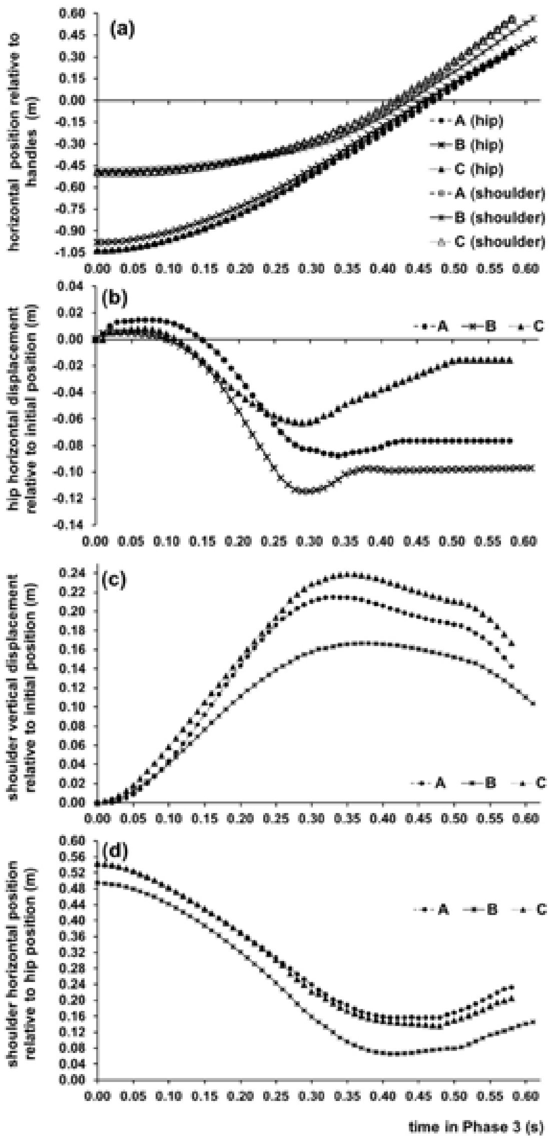
The final position of the shoulders was equal for all athletes, so at the moment when releasing the handles the differences among athletes in terms of body position were only observed in the hip's horizontal position. Athlete C had a lower vertical initial position of the shoulders then the other two athletes (0.16 m above the start handles), but the shoulders' horizontal position was similar for all athletes.

Figure 3 demonstrates hip and shoulder position in Phase 3 with respect to the phase's duration. In accordance with the velocities exhibited in Figure 2 (b) and (d), athlete B tended to have larger hip displacement relative to initial position, less overall shoulder vertical displacement, and a closer shoulder horizontal position in relation to the hip (Fig. 3b and d). At around half of Phase 3's duration the differences between the three

Table 3. Hip and shoulder mean kinematics during Phase 3 (mean ± SD)

	A	B	C
Hip initial horizontal position (m)	–1.04 ± 0.00	–0.98 ± 0.02	–1.04 ± 0.01
Shoulder initial vertical position (m)	0.20 ± 0.01	0.22 ± 0.01	0.16 ± 0.00
Shoulder initial horizontal position (m)	–0.50 ± 0.00	–0.49 ± 0.01	–0.49 ± 0.01
Hip end horizontal position (m)	0.33 ± 0.03	0.42 ± 0.02	0.35 ± 0.05
Shoulder end vertical position (m)	0.34 ± 0.01	0.33 ± 0.01	0.33 ± 0.02
Shoulder end horizontal position (m)	0.56 ± 0.00	0.56 ± 0.01	0.56 ± 0.02
Distance travelled by hip (m)	1.37 ± 0.03	1.40 ± 0.01	1.39 ± 0.05
Maximal hip negative displacement relative to the sled (m)	0.11 ± 0.02	0.12 ± 0.02	0.07 ± 0.02
Maximal hip-shoulder horizontal distance (m)	0.54 ± 0.00	0.49 ± 0.02	0.54 ± 0.00
Minimal hip-shoulder horizontal distance (m)	0.15 ± 0.03	0.07 ± 0.02	0.13 ± 0.06
Maximal shoulder vertical position (m)	0.41 ± 0.00	0.39 ± 0.01	0.40 ± 0.00

Hip and shoulder position is indicated relative to the start handles' position.



(a) hip and shoulder horizontal position relative to the start handles
(b) hip horizontal position relative to initial position
(c) shoulder vertical position relative to initial position
(d) shoulder horizontal position relative to hip position

Figure 3. Averaged joint position with respect to Phase 3 duration

athletes in hip placement relative to the handles position became indistinguishable; only the horizontal placement of athlete's B shoulder showed a small difference in comparison to the other two athletes (Fig. 3a).

Discussion

The start of a luge run is a complex movement process that consists of several phases, where the main objective of pushing-off from the handles is to accelerate the sled to the highest possible velocity. Athletes begin this forward motion with their knees bent and torso leaning forward to allow for a powerful initial pull on the start handles, and then, when the sled is leaving the horizontal start platform, continue the gained momentum by pushing off the handles as hard as possible. Ideally, the transfer from pulling to pushing should occur without, or with relatively small, losses in the sled's velocity, so that the final push-off would lead to an overall increase in sled velocity.

However, the results showed that, in reality, the examined athletes deviate from this ideal model and by the end of Phase 3 lose 12% to 15% of the maximum achieved sled velocity. These findings are in agreement with data collected on male lugers by Platzer et al. [9]; male lugers underwent a similar drop from maximum attained sled velocity after push-off from the start handles at about 0.50 m · s^{-1}, corresponding to around 12% drop in maximum sled velocity.

Despite the different techniques that were observed in the current study in attaining maximum sled velocity development (Fig. 2), all athletes had an almost similar drop in maximum sled velocity (Tab. 2). A small exception was seen in athlete C, who had reached maximum sled velocity just before releasing the handles and had, therefore, a smaller loss in velocity.

The technique behind athletes' A and B start velocity was similar, as both athletes had similar sled velocity curves and also featured similar drops in sled velocity that occurred in two points in time during the examined start phase. The first sled velocity loss for athletes A and B occurred immediately after attaining maximum sled velocity, and was associated with a decrease in hip and shoulder vertical velocity. This might indicate that at this point in time there is a decrease in the strength of the arms' pull and the push by the feet. The athletes' maximum sled velocity came from the initial pull on the start handles; both athletes reached their maximum sled velocities in the same hip position – 0.65 m behind the start handles and it took athlete B 0.24 s and athlete A 0.26 s from the forward movement to reach it. The kinematics of their hip and shoulder movement at this moment were similar in character. The peak was reached during a decreasing, but still positive slope of the vertical shoulder velocity curve, shortly after hip minimum horizontal velocity (relative to the sled) was achieved. This points to the fact that the hips backward movement is associated with an extension of the knees when athletes are pushing on the foot supports with their feet. Athletes reached their maximum sled velocity with a strong back extension, where the shoulders were moving horizontally backwards at their fastest pace. Athlete's B lower vertical shoulder velocity is probably the result of weaker back extensors, hence the lower maximum velocity of the sled when compared to athlete A. On the contrary, athlete A initiated the pull with a faster backwards shoulder movement and having lower vertical movement velocity, optimizing in this way the horizontal pull, which allowed her to quickly gain vertical velocity and thereby achieving the fastest sled velocity.

The decrease in the sled's horizontal velocity lasted until the shoulders reached a maximum plateau in the vertical position, when the hips reached a maximum backward position relative to initial position on the sled. Athlete A had a shorter and smaller sled velocity drop; the velocity of the sled was stabilized when shoulder horizontal backward velocity began to decrease and hip relative velocity was close to zero. Athlete B, having a less pronounced drop in the decrease in vertical shoulder velocity and a larger hip backward velocity, demonstrated a longer and larger sled velocity decrease. During this decrease, athlete's B hips transferred from backward to forward horizontal velocity relative to the sled. After the sled's velocity decrease, athlete B had another attempt to gain velocity following the hips maximum positive horizontal velocity.

Athlete C had the same technique for increasing sled velocity. Unable to produce enough momentum to reach a high initial sled velocity (this was accompanied by a low backward velocity of the hips and a plateau in shoulder vertical velocity), she gained horizontal velocity of the sled by moving the hips forward on the sled, when the shoulders reached the maximum vertical position and had passed the start handles.

The drop in sled velocity for athlete C occurred in the same conditions as the second drop for athletes A and B, when the hips were crossing the start handle and the upper body began to be lowered. This is the point when athletes transfer to the push-off from the handles and are supposed to gain sled velocity using the drive from the push-off (Fig. 2 and 3). Failure to do so might indicate incorrect technique or a weak wrist flexion and arm extension, as described by Platzer et. al. [9].

In terms of the positioning of the analysed body segments, at the beginning of the start phase each athlete placed her hips and shoulders repeatedly at the same distance from the start handles, which indicates constancy in technique. At the instant when they push-off from the handles, each athlete again maintained a similar position of the shoulders, where any variations of their technique that slightly exceeded measurement error (athletes A and C) only appeared in horizontal positioning of the hips (Tab. 3). This is explained by different shoulder horizontal velocities (relative to hip velocities) that the athletes have during release. Athlete A, with the highest shoulder positive horizontal velocity ($0.77 \text{ m} \cdot \text{s}^{-1}$ relative to hip velocity), had her shoulders farther in front of the hips than the other two athletes. Athlete B, exhibiting the lowest shoulder horizontal velocity, had the smallest horizontal distance between her hips and shoulders (Tab. 2 and 3).

The numerous similarities in the positioning of the shoulders between the three athletes and the more significant differences found in hip positioning and relative movement on the sled point to the importance of knee extension with a backwards hip movement in accelerating the sled to a high velocity. Therefore, the influence of the hips' movement during the start should not be underestimated.

This study has demonstrated that the athletes use at least two techniques to increase sled horizontal velocities: first by pulling on the start handles with a forceful back extension and with their feet pushing on the support, and then by sliding the hips forward on the sled and attempting to increase the forward slide of the sled. A combination of these techniques of velocity development is possible and might be beneficial for promoting sleds' horizontal movement.

Also two weak points where sled velocity loss is possible have also been observed. One occurs immediately after the initial pull on the handles and is most probably the result of a decrease in the strength of the pull and transfer to forward motion of the body. The second weak point occurs at the moment when the sled velocity increase would be expected in an ideal model – when pushing off the handles. Strengthening the wrist muscles might be an option for overcoming this limitation.

In order to improve the level of start performance, kinematical conditions, in which athletes gain or lose velocity of the sled, should be taken into consideration both from a technical and conditioning point of view.

Conclusions

The study has shown that the athlete and the sled do not move as a whole rigid system, and there exists hip movement relative to the sled. This hip movement has an important role in the development of the initial velocity of the sled, and the importance of this movement is comparable to the importance of back extension movement.

The athletes used at least two techniques for increasing the horizontal velocity of the sled. The first one is by pulling on the start handles at the beginning of the start phase, where an increase in the speed of the hips' backwards movement relative to the sled and the vertical movement of the shoulders appears to be more beneficial in achieving higher horizontal sled velocity. The second technique is in pushing the hips forward on the sled when the shoulders reach their maximum vertical position as an attempt to increase the forward momentum of the sled itself. A combination of both tactics might allow one to gain an even greater horizontal velocity of the sled.

There were also two instances of velocity losses observed – when transferring from the initial upwards torso movement to the forward movement and at the push-off phase from the handles. The latter was previously believed to provide a gain in horizontal sled velocity, but weakness in wrist flexion or arm extension, as well as incorrect technique, could impede this push-off movement. Additional studies that research larger pulls would bring greater understanding of the interactions between the above-mentioned factors and how they can be better optimized to bring sporting success.

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