GIVING THE FORCE DIRECTION: ANALYSIS OF SPEED SKATER PUSH OFF FORCES WITH RESPECT TO AN INERTIAL COORDINATE SYSTEM.

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Push-off in speed skating requires an extensive motion strategy. During speed skating the skater continuously changes the lean and steering angle of the skate and therewith the direction of push-off. The forces in an inertial coordinate system can give insight into what amount of the push-off force is directed into the forward motion. In this paper we present the preliminary results of a study on the global forces in speed skating. From a mechanical viewpoint, increasing the lean angle of the skate seems beneficial at the end of the stroke, but detrimental at the start of the stroke. Furthermore the necessity of the lateral force on the skate in the overall force production is a variable of interest for further investigation, since dynamically it has a disadvantageous effect on the forward motion.

KEY WORDS: Speed Skating, Winter Sports, Kinematics, Kinetics, Power.

INTRODUCTION: Push-off in speed skating requires an extensive motion strategy. We would like to provide speed skaters and coaches with feedback to improve their technique within an individual skating stroke, thus we need to determine which factors influence the performance. The performance criterion is the forward velocity of a speed skater in longitudinal direction of the track. Previous studies on performance on the level of an individual skate stroke can be divided into studies on opposing forces (friction) [1], [2] and studies on power generation. This latter category can be divided into studies on the power generation by the joints [3], [4] and measurements of reaction forces on the skate [5]–[8]. Power generation in the joints does not provide insight into what part of the power is generating the forward motion in line with the track. The push-off force of a skater pushes him in both the sideways and forward direction of the rink, but performance is measured in the forward direction only. It therefore seems important to take this separation into account. Previously, the forces measured on the skate have been projected as a vertical and horizontal component [5], [6]. However the steering angle, and therefore the division of the horizontal force into a forward and sideways direction, was omitted.
The orientation of the skate with respect to an inertial system can be used to express the locally measured normal and lateral forces (F_N, F_L (Figure 1F)) into the global inertial system (F_x, F_y, F_z). The global forces can give insight into what amount of the push-off force is directed into the forward motion (x). Hypothesized is that these forces will provide skaters and coaches with insight on their performance. In this paper we present the preliminary results of a study on the global forces in speed skating.

METHODS: The experiment took place in January 2015 on the Dutch indoor ice rink of Thialf Heerenveen. Kinematic data were captured by twenty Qualisys motion capture cameras, positioned along the straight part of the rink in a volume of 50x5x1.5m^3 [9]. The participants were equipped with full body marker sets consisting of 21 passive markers. The velocity of the torso, determined by four markers on the upper body, was used to determine the skaters' velocity. In this paper the data of the right strokes of four elite speed skaters (two male, two female) are employed. The average velocity of the strokes and the number of strokes used in this paper are shown in Table 1. The forces on the skate in normal and lateral direction and the point of force application on the blade were measured by two instrumented klapskates, on which the participants placed their own shoe and skating blades [8]. The forces in line with the skate blade were assumed to be less than 1% of the normal force and were therefore neglected. The Qualisys and Instrumented skate data were synchronized via a digital start-and-end pulse [10]. The rotation matrices of the skate were constructed based on the four markers on the skate by the program Visual 3D. The forces measured on the skate were rotated into a global coordinate system via these rotation matrices.

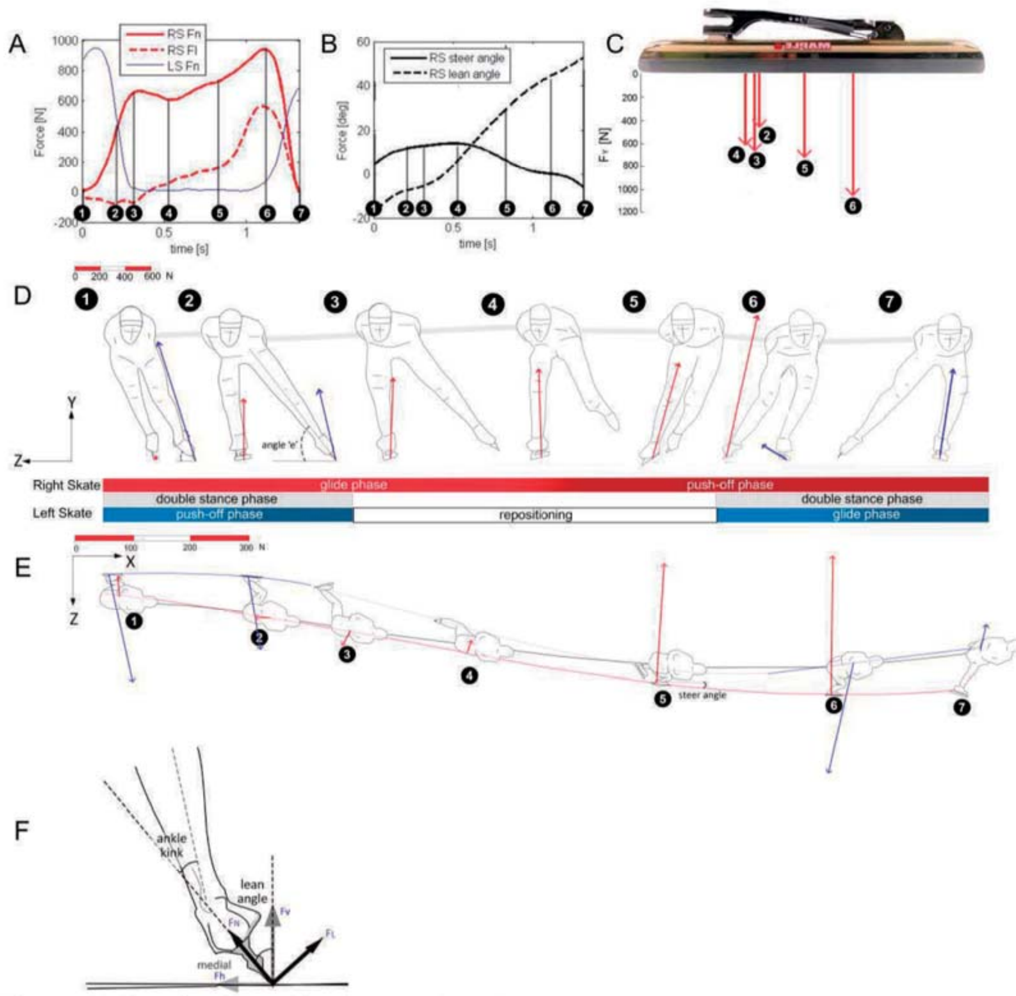

Figure 1: A typical coordination pattern of a speed skater. A-E: 1) The skater places the right skate on the ice, while the normal force on the left skate almost reaches its peak value. 2) The weight of the skater is evenly divided over the left and right skate. 3) All the weight is shifted to the right skate, the left skate is retracted from the ice, which ends the double stance phase. 4) The skater lowers his upper body by decreasing the knee angle. Lowering the upper body causes a dip in the normal force curve of the skate. In this phase, the gliding phase, the lean angle transforms from negative to positive, so the skate shifts from the lateral to the medial side of the blade. The steering angle of the skate is at maximum when the lean angle is zero. 5) The skater moves his upper body away from his skate, thereby increasing the force on his skate. Since the lean angle is now positive and also the steering angle still has a positive angle, the skater has a force component in both the forward and the sideways direction of the rink. 6) The skater keeps increasing his force, by stretching his knee (push-off phase), until the peak force. Just before the peak, the left skate re-entered the ice. 7) The skater shifts his weight to the left skate, until all weight is shifted and the skater retracts his skate from the ice. The skater then repositions his right skate for the next stroke. During the stroke the upper body of the skater has an up-and down movement of about 0.15 m. The distance covered in this stroke was 12.6 m. C: the centre of pressure (COP) of the measured forces for point 2-6 (points 1 and 7 have too little force on the skate, to determine the COP). F: The local measured forces are the normal (F_N) and lateral (F_L) force.

Table 1 Characteristics of the participants. BW = ratio of body weight .

Participant	Mass (kg)	# of strokes	Velocity Y (m/s)	Peak F_N (BW)	Peak F_L (BW)
P1 (♀)	70	N = 4	9.7(±0.12)	1.49 (±0.09)	1.09 (±0.14)
P2 (♀)	65	N = 11	9.7(±0.55)	1.44 (±0.09)	1.06 (±0.17)
P3 (♂)	76	N = 3	11.0(±1.1)	1.32 (±0.07)	1.05 (±0.21)
P4 (♂)	81	N = 6	11.0(±0.45)	1.35 (±0.03)	0.57 (±0.11)

The performance of a speed skater is determined by the forward velocity in longitudinal direction of the track (x). This velocity is generated by the push-off force of the skater thereby opposing the frictional forces of air and ice. The lean and steering angle divide these locally measured forces (F_N and F_L) into the global coordinate system (F_x, F_y, F_z) (Figure 1F). The lean angle of the skate divides the normal and lateral force in a horizontal (F_h) and vertical (F_v) component (Figure 1F). The horizontal component drives the skater. F_h always acts perpendicular to the skate blade, since a push-off in line of the blade is restricted due to the slippery ice. F_h can be determined by

$$F_h = F_N \sin(\varphi) - F_L \cos(\varphi) \tag{1.1}$$

Where φ is the lean angle of the skate. The steering angle divides this horizontal force into the forward direction of the track (x) and the sideward direction (z) (figure 1E) via

$$\begin{aligned} F_x &= \sin(\theta) \cdot F_h \\ F_z &= k \cdot \cos(\theta) \cdot F_h \end{aligned} \tag{1.2}$$

Where θ is the steering angle of the skate and $k = -1$ for the right stroke and $k = 1$ for the left stroke. A steering angle steers the skater to the side of the track and therefore seems adverse for the forward movement. However, without any steering ($\theta = 0$) there is no force in the x-direction. Therefore the skater has to do a trade-off between forward push-off and gliding.

RESULTS AND DISCUSSION: Figure 1 shows a typical coordination pattern of a speed skater and the force vectors, measured in this study. The skating stroke, motion pattern and the stroke phases are explained in the caption.

The performance of a speed skater is determined by the forward velocity in longitudinal direction of the track (x), which is generated by the force F_x. Therefore by increasing F_x, the forward velocity and thus performance will improve (assuming the frictional forces do not change). Since the steer angle (θ) is positive during the majority of the stroke (Figure 1B), formula 1.2 tells us that F_h needs to increase to obtain a larger F_x. Formula 1.1 shows how to compose F_h out of the local forces on the skate, F_N and F_L, and the lean angle of the skate, φ. While φ is positive, F_N has a positive relation to F_h, while F_L has a negative connection to F_h. Contrary, while φ is negative, which occurs at the start of the stroke, F_N has a negative relation to F_h, while F_L still has a negative connection.

The results show that F_N is always positive (Figure 1A). Therefore an increased normal force improves the forward force F_x, except for the start of the stroke, where the lean angle is negative. Here F_N should be minimized or the negative φ should be minimized. We suspect that the negative lean angle at the start of the stroke helps the skater to steer his skate (Figure 1E). The steering and leaning of the skate have a distinct relation. It seems impossible to change the direction of the skate during motion while the skate is upright.

The lateral force F_L is positively related to the lean angle of the skate for each participant ($p<0.00$, $R=0.9$). So when φ is positive, F_L is positive. Since F_L always has a negative relation to F_h, F_L then has an adverse effect on the forward force F_x. From a mechanical viewpoint is seems therefore beneficial to minimize the lateral force for this part of the stroke (while φ is positive). At the start of the stroke, where φ is negative, the then negative F_L has an advantageous effect on F_h and thus F_x. The authors expect that the lateral force might be related to the ankle kink of the skater (Figure 1F), but this needs further investigation. Furthermore, from a physiologic stance, it might be disadvantageous or even impossible for a skater to adjust the lateral force on the skate. A complete biomechanical model of the speed skater should give a decisive answer on this matter[11].
The previous discussion on the transformation from a local force system to the global forces emphasizes that a high level of force application on the skate is not a guarantee for a high performance [7]. However the preliminary results in the current study do show that there is a significant within-subject relation between the normal peak forces F_N and the speed (P2: $p=0.01$, $R = 0.73$; P4: $p=0.03$, $R=0.84$). That is saying a good deal that an individual can increase his velocity by increasing his push-off force, but that the force production does not determine the performance between speed skaters.

CONCLUSION: The performance of a speed skater is determined by the forward velocity in longitudinal direction of the track (x). During speed skating the skater continuously changes his lean and steering angle of the skate and therewith the direction of push-off. The preliminary results in this study show that analysing the steering and lean angle in speed skating can benefit the understanding of the speed skating motion. From a mechanical viewpoint, increasing the lean angle of the skate seems beneficial at the end of the stroke, but detrimental at the start of the stroke. Furthermore the necessity of the lateral force on the skate in the overall force production is a variable of interest for further investigation, since dynamically it has a disadvantageous effect on the forward motion.

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