Potential Method of Optimizing the Klapskate Hinge Position in Speed Skating

Scott Van Horne and Darren J. Stefanyshyn
University of Calgary

Acceptance of the klap speed skate was fully realized on the world speed skating scene in 1997. However, one of the most important unknowns regarding the klapskate was the positioning of the point of foot rotation (pivot point), which is believed to play an important role in optimizing klapskate performance. The purposes of this study were to explore the ankle, knee, and hip joint mechanical changes that occurred when the pivot point location was modified, and to determine whether maximal ankle torques provide predictive ability as to where the optimal pivot point positioning is for a skater. We tested 16 proficient skaters at three pivot point (PP) locations, ranging from just in front of the metatarsal-phalangeal joint to just in front of the first phalangeal joint. Of the 16 skaters, 10 were tested at a fourth position: tip of the toe. Push phase kinetics and kinematics were measured on a modified slide board. The optimal PP for each skater was defined as the position that allowed him to generate the most total push energy. Maximum voluntary static torque measures of the ankle and knee were collected on a Biodex dynamometer. Overall, anterior pivot point shifting led to a significant increase in ankle energy generated and a decrease in knee energy generated, with no significant change at the hip joint. We found no significant correlations between the static strength measures and the skaters’ optimal pivot points.

Key Words: pivot point, energetics, performance

Speed skating has seen many innovations in the last 8 years. The most noteworthy is the klapskate. Until 1997 all world class skaters skated on conventional speed skates that had the blade firmly fixed to the bottom of the boot, even though a more efficient technology known as the “klapskate” had been invented almost 100 years before (Gemser & Kristiansen, 1999). The klapskate is a skate that permits the shoe to rotate on a hinge relative to the blade. This allows plantar flexion with the blade remaining flat, gliding on the ice. It has been shown that the resultant push force moves forward on the skate blade throughout the first 75% of the explosive push phase, until it reaches the klapskate hinge where it remains for the final 25% (Houdijk, de Koning, de Groot, Bobbert, & van Ingen Schenau, 2000a).

The authors are with the Human Performance Laboratory, University of Calgary, 2500 University Drive N.W., Calgary, Alberta T2N 1N4, Canada.
Conversely, with the conventional non-klap speed skate, the resultant push force continues to move forward on the blade until it reaches the front end of the blade (Houdijk et al., 2000a). It was found through experimental and practical means that the klapskate increases skating velocity by 3–5% which can almost entirely be accounted for by the 7–12% increase in mechanical power output, which is possible because of an increase in mechanical efficiency (de Koning, Houdijk, de Groot, & Bobbert, 2000; Houdijk et al., 2000a; Houdijk, de Koning, & van Ingen Schenau, 1998; Houdijk, Heijnsdijk, de Koning, de Groot, & Bobbert, 2000b; van Ingen Schenau, de Groot, Scheurs, Meester, & de Koning, 1996). When the klapskate was re-engineered in 1985 it was not known where to position the hinge of the klap mechanism, which is the point of foot rotation (pivot point), so it was arbitrarily placed just behind the first phalangeal joint.

Since the klapskate became commercially available in 1997, different manufacturers have made the pivot point placement adjustable, but there is still no scientific reasoning as to where one should put the pivot point to attain optimal performance. A few studies have tried to quantify an optimal pivot point (PP) but they all found inconsistent results and pronounced individual differences (Allinger & Motl, 2000; Bobbert, Houdijk, de Koning, & de Groot, 2002; Houdijk, de Koning, de Groot, & Bobbert, 1999; 2002). For the purposes of this study the optimal PP was assumed to be the position that allowed the skater to generate the most total work during the explosive push phase. Work per stroke has been found to be higher for elite skaters compared to trained skaters and was associated with the increased performance of elite skaters (de Boer, Vos, Hutter, de Groot, & van Ingen Schenau, 1986), suggesting that it is one of the most important performance variables. During the final 50 ms of the push phase, while the foot is rotating, PP positioning has an effect on the push mechanics (Houdijk et al., 2000a; 2002). As the PP is moved forward, the lever arm between the ankle joint and the line of action of the push force is increased (Figure 1). PP placement appears to have an effect on the flexion moment at the knee joint, when push energy is absorbed. During the early phase of the push when the knee extensor muscles are generating large extension moments at the knee, the foot has not yet begun to rotate and PP placement has no effect (Houdijk et al., 2000a; 2002).

When in the push phase the foot begins to rotate, the knee extension moment is very close to zero and soon afterward the force generated by the knee flexor muscles creates a resultant knee flexion moment (Houdijk et al., 2000a; 2002). This resulting knee flexion moment ensures that the knee does not hyperextend but also absorbs energy from the push phase. Hip joint kinetics would be least affected by PP positioning because the hip joint center is relatively close to the body’s center of mass in the skating position, given that the line of action of the ground reaction force has to go through the body’s center of mass to prevent rotation of the trunk. Therefore the lever arm formed between the line of action of the push force and the hip joint would be minimally affected (van Ingen Schenau & Bakker, 1980).

Theoretically, PP placement should have the largest effect on positive joint work and torque at the ankle. It was speculated that an individual with higher plantar flexor capacity to generate torque and do work would perform optimally with a more anterior placed PP. This is based on the assumption that the plantar flexors are not maximally contracting at the more posterior PP positions. If the plantar flexors were maximally contracted, the moment generated by the muscles about the ankle joint would prematurely overcome the external moment about the joint,
resulting in premature opening of the klap mechanism and a shortened push. Thus if a skater has additional potential for force generation from the plantar flexors, an anterior PP should result in an increased torque, with only a minimal decrease, if any, in angular velocity and a resultant overall increase in power at the ankle joint. The opposite would be true for individuals with lower plantar flexor capacity because the smaller plantar flexor torque would delay foot rotation and result in inefficiently high knee and hip extension velocity, coupled with excessively low joint torque, and inefficiently low ankle plantar flexion velocity, resulting in reduced energy production.

The primary purpose of this study was to explore the ankle, knee, and hip joint mechanical changes that occur when the pivot point is modified. The secondary purpose was to determine whether there is a relationship between the speed skater’s capacity to generate ankle plantar flexor torque and his or her optimal pivot point location. It was hypothesized that skaters who are capable of generating higher ankle plantar flexor torque would have a more anterior optimal pivot point.

### Methods

Sixteen participants were selected through volunteer recruitment. A sample size calculation was executed (power = 0.8) with the mean differences found at the ankle joint in a study by Houdijk et al. (2002), and a sample size of 11 was recommended. Sixteen participants were used in this study to help ensure that significant differences would be found where real differences existed.

All participants in this study were male, proficient skaters, with personal best times within 10% of the world record. They were between 18 and 35 years of age.
Informed written consent, in accordance with the University of Calgary’s Research Ethics Board, was obtained from all participants.

Due to the difficulties and errors associated with on-ice kinetic and kinematic testing, the current study aimed to reproduce a speed skating push as close as possible to the actual skating movement, in the lab where limits on equipment use are reduced and a more controlled environment can be utilized. To date there have been a limited number of speed skating models that encompass off-ice testing (Allinger & Motl, 2000; Allinger & van den Bogert, 1997; Bobbert et al., 2002). In fact, other than a few computer simulation models, the only off-ice models are one-footed vertical jump tests, analyzed with inverse dynamics. A limitation of the vertical jump test is that the jump is a more explosive movement than the skating push. The skating push is more controlled because the fall sideways must be timed with the joint extension so that the center of mass (CM) does not move up vertically. A jump model also lacks the hip abduction (exorotation) present in the skating push, and the jump test cannot be safely performed while wearing a speed skate.

The concept of the model used in this study is rooted in a very well known and practiced off-ice training apparatus: slide board skating. An important aspect present in the slide board model is that the push force is in the same direction as the push force during on-ice skating. This leads to a translation of joint energetics into center-of-mass velocity in the same direction (horizontal) as in on-ice skating, contrary to the jump model wherein the center-of-mass velocity is directed vertically.

In a study by Kandou, Houtman, Bol, et al. (1987), maximal exercise tests were performed on the ice and on a slide board (referred to as a skateboard in the study) to compare different kinematic and physiological variables. It was found that heart rate values, oxygen uptake, and respiratory exchange ratios were not significantly different. Also, angular position, velocity, and acceleration were plotted vs. time for the hip and knee, indicating very similar trends.

The modified slide board model was set up as follows: a small block of wood was placed near the end of a 6.1m × 1.2m melamin sheet. The participant performed the simulated skating push from the block of wood. From this point he slid along the board until friction stopped him. The slide board was surrounded by 7 high-speed digital cameras at the location of the board where the pushes occurred. The block of wood was attached directly to the force plate, with a 7.5-cm gap between the melamine sliding component and the block of wood, so as to eliminate any connection the support leg would have with the force plate. The pushing foot was in a speed skate that had a protective low-resistance material under the blade so that the blade and slide board were not damaged. The contralateral foot was clad in a running shoe covered with a wool sock. The modified slide board setup is shown in Figure 2.

To investigate optimal pivot point (PP) placement, we tested three different PP conditions: 55%, 62.5%, and 70% of the total length of the skate boot, measured horizontally in the sagittal plane, extending from the ankle joint center to the PP (ankle lever in Figure 3). Ten of the 16 participants had data collected on an additional PP condition: ankle lever of 77.5% of the total skate boot length. This position could not be tested on all skaters because of limitations in the movement range of the mechanism resulting from large foot sizes. Houdijk et al. (2002) employed a similar method of PP placement over a smaller range (57% to 73%). It should be noted that the average PP placement as set by the initial klapskate manufacturers
is 63% (Houdijk et al., 2000a). Ten trials per condition per participant were conducted. Condition orders were randomly assigned. Each trial consisted of a maximal push on the modified slide board, followed by 1 to 2 minutes rest. Each participant underwent the slide board trials with his own speed skate boot and a modified klap mechanism that allowed for an average 63-mm range of PP movement. Current commercial klap mechanisms have a range of PP movement of approximately 20 mm. All participants had used the traditional slide board as an off-ice training tool. In addition, during the week prior to data collection they were asked to come to the lab and practice on the modified slide board setup for 30 minutes.

Kinetic data were collected with a force plate (Kistler, Winterthur, Switzerland) sampling at 2,400 Hz. Kinematic data were collected simultaneously using a 7-camera system (Motion Analysis Corp., Santa Rosa, CA) sampling at 240 Hz. Reflective markers 1 cm in diameter were placed superficially on the medial and lateral malleoli and the medial and lateral epicondyles of the right leg to mark the joint centers during initial neutral trials recorded prior to the experimental trials. The midpoints of these markers were used to identify the ankle and knee joint centers,
respectively. For the right hip joint center, a marker placed on the greater trochanter identified the position in the sagittal plane while a marker on the anterior superior iliac spine identified the mediolateral position.

In the neutral trials, participants were required to stand with feet shoulder-width apart aligned with the lab coordinate system in the anterior-posterior direction to reference the experimental markers with the joint centers. During the neutral and experimental trials, three 1-cm diameter markers were placed in a triangular pattern on each of the skate boot, shank, thigh, and torso (Figure 2). Anthropometric data were collected including participant height and mass as well as the lengths of each of the foot, shank, thigh, and torso segments. Relative mass and center of mass were calculated using regression equations from Clauser, McConville, and Young (1969), and moments of inertia were calculated using regression equations from Dempster (1955). Analyses were performed after smoothing both the video data and the force data via fourth-order low-pass Butterworth filter (cutoff frequency 10 Hz for video and 100 Hz for force data).

Inverse dynamics with a rigid link segment model was used to obtain instantaneous resultant joint moments. Instantaneous joint power was calculated by taking the dot product of the instantaneous resultant joint moment vector by the instantaneous joint angular velocity vector. All kinematic and kinetic analyses were done with Kintrak software (Human Performance Laboratory, Calgary). The movement analyzed started from a simulated glide phase where all the joints of interest were in a flexed position. Throughout the movement these joints extend, and therefore all resultant extensor moments were considered positive. Joint energy per push was calculated by integrating the power-time curves between push-start and push-end. Total energy per push (TE) was the sum of ankle, knee, and hip joint energy during the explosive push phase.

Push-start was defined as the instant when the knee angular velocity exceeded 90°/s, a value previously used in the literature to identify the start of the explosive push phase (Houdijk et al., 2002). Push-end was defined as the instant when the resultant push force, in the horizontal direction, dropped to zero. It has been shown in the literature that extreme modification of the PP has no effect on the number of strides executed in a straightaway. Therefore it is speculated that any changes in the timing of the push phase, as a result of PP modification, are compensated for during the recovery phase (Houdijk et al., 2000a).

Physiological data of the ankle and knee were collected on a Biodex dynamometer (Biodex Medical Systems, New York). Maximum voluntary isometric muscular contractions were collected. Participants were secured in the Biodex machine using restraining belts to isolate the joint of interest. Joint angles used for the isometric contractions were determined from the slide board data. The skater’s joint angles at the point of peak power in the push phase were averaged for the different joints, and that angle was used. Three repetitions of maximum isometric contractions during ankle and knee joint extension were executed and held for 3 seconds, followed by 1-minute rest intervals between repetitions. Data were collected at 100 Hz. Average peak torque was calculated for the three trials and normalized to body mass.

The participants’ normalized ankle and knee peak torque values were then correlated with their optimal pivot points to determine whether the tested physiological values provided a valid indication of individual pivot point location for optimal performance.
A one-way repeated-measures ANOVA was used to compare, both within and between participants, the change in joint energy and the change in total push energy between the different PP conditions. Post hoc analysis consisted of two-tailed paired \( t \)-tests. Correlation coefficients were determined from a comparison between the optimal PP conditions and the physiological data of the parts. In all tests, \( \alpha \leq 0.05 \) was chosen for statistical significance.

**Results**

All participants were tested at the 55%, 62.5%, and 70% conditions \( (N = 16) \). A full kinetic and kinematic analysis is presented in Table 1. Knee and hip range of motion increased significantly, by 4.4 and 4.0% respectively, when the PP was shifted anteriorly. This was coupled with a significant increase in peak angular velocity at the knee and hip, 1.9 and 3.4% respectively, when the PP was moved from the 55% condition to the 62.5% condition. A significant decrease (4.5%) in peak angular velocity was seen at the ankle joint when the PP was moved anteriorly from the 62.5% to the 70% condition. The energy produced at the ankle joint, throughout the explosive push phase, increased significantly (10.6%) when the PP was moved anteriorly, whereas the energy produced at the knee joint decreased significantly by 31.8%. Total energy per push (TE) did not show any significant differences at the three PP conditions. Push impulse was also not significantly different between conditions (Table 1).

**Table 1**  **Mean Values \( (N = 16) \) and Standard Deviations for the 55, 62.5, and 70% Pivot Point Conditions**

<table>
<thead>
<tr>
<th>Variable</th>
<th>55%</th>
<th>62.5%</th>
<th>70%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Push duration (ms)</td>
<td>144 ± 25</td>
<td>147 ± 22</td>
<td>150 ± 20</td>
</tr>
<tr>
<td>Peak ankle angle (°)</td>
<td>126.2 ± 7.2</td>
<td>126.4 ± 8.7</td>
<td>124.4 ± 8.9</td>
</tr>
<tr>
<td>Peak knee angle (°)</td>
<td>162.5 ± 7.1</td>
<td>164.9 ± 7.4</td>
<td>164.7 ± 7.8</td>
</tr>
<tr>
<td>Peak hip angle (°)</td>
<td>100.4 ± 10.9</td>
<td>102.8 ± 10.3</td>
<td>103.2 ± 10.0</td>
</tr>
<tr>
<td>Ankle ROM (°)</td>
<td>53.8 ± 6.7</td>
<td>54.9 ± 8.4</td>
<td>53.7 ± 8.5</td>
</tr>
<tr>
<td>Knee ROM (°)</td>
<td>65.2 ± 6.8</td>
<td>67.3 ± 7.6</td>
<td>68.0 ± 7.7</td>
</tr>
<tr>
<td>Hip ROM (°)</td>
<td>42.0 ± 4.8</td>
<td>43.3 ± 4.8</td>
<td>43.7 ± 4.4</td>
</tr>
<tr>
<td>Maximum ankle ( \omega ) (°/s)</td>
<td>847.9 ± 123.4</td>
<td>860.6 ± 126.0</td>
<td>821.8 ± 107.0</td>
</tr>
<tr>
<td>Maximum knee ( \omega ) (°/s)</td>
<td>745.2 ± 93.6</td>
<td>759.4 ± 96.0</td>
<td>748.8 ± 87.0</td>
</tr>
<tr>
<td>Maximum hip ( \omega ) (°/s)</td>
<td>389.0 ± 70.4</td>
<td>402.2 ± 62.8</td>
<td>407.7 ± 63.1</td>
</tr>
<tr>
<td>Ankle energy (J)</td>
<td>49.4 ± 9.7</td>
<td>53.3 ± 10.6</td>
<td>54.7 ± 10.8</td>
</tr>
<tr>
<td>Knee energy (J)</td>
<td>23.1 ± 12.1</td>
<td>19.1 ± 11.5</td>
<td>15.8 ± 11.6</td>
</tr>
<tr>
<td>Hip energy (J)</td>
<td>28.5 ± 11.4</td>
<td>28.8 ± 10.6</td>
<td>28.6 ± 11.1</td>
</tr>
<tr>
<td>TE (J)</td>
<td>101.0 ± 17.5</td>
<td>101.0 ± 16.4</td>
<td>99.0 ± 16.1</td>
</tr>
<tr>
<td>Push impulse (N·s)</td>
<td>85.0 ± 21.8</td>
<td>85.0 ± 20.1</td>
<td>83.9 ± 20.4</td>
</tr>
</tbody>
</table>

*Note:* Indicates a significant difference: \(^1\)from the 55% condition; \(^2\)from the 62.5% condition; \(^3\)from the 70% condition.
Six of the 16 participants had their optimal PP condition at the 55% location. Seven skaters had an optimal PP location at 62.5%, and the remaining 3 skaters had an optimal PP location at 70%. None of the 10 participants who were tested in the 77.5% condition generated the most total work at this location during the speed skate push.

Maximal TE values for each skater were correlated with their best previous season 500-m race times, to further test the effectiveness of the modified slide board in replicating on-ice skating performance (Figure 4). TE had a large significant correlation with 500-m race time ($R = -0.81$). No significant correlations were found between optimal pivot point location and normalized ankle or knee torque obtained from the Biodex measurements (Figure 5).
Discussion

The primary purpose of this study was to assess the ankle, knee, and hip joint mechanical changes that occur when the pivot point is modified. Shifting the PP had systematic effects on joint kinematics that closely resembled what was found in the literature (Houdijk et al., 1999; 2000a; 2002). The current study found that anterior movement of the PP caused a significant increase in knee and hip ranges of motion and peak angular velocities, along with a decrease in ankle angular velocity. Similar results were found with the klapskate/conventional skate comparison study (Houdijk et al., 2000a) and with two other studies in which the PP was shifted between conditions (Houdijk et al., 1999; 2002). A systematic decrease of 7.3 joules in knee energy was found with anterior shifting of the PP from the 55% to the 70% condition. Houdijk et al. (2002) also found a significant decrease of 5.3 joules at the knee joint, between positions comparable to the 55% and 70% conditions. That study also found a 3.7-joule increase in ankle energy between the 55% and 70% comparable conditions, but the change was not significant (Houdijk et al., 2002). The present study found similar but more systematic and significant differences of 5.2 joules at the ankle joint, between the 55% and 70% conditions.

It was shown in the literature that anterior shifting of the PP, which increases the moment arm between the ankle joint and the resultant push force, caused a delayed onset of foot rotation (Houdijk et al., 2002) beyond a point in the range of the 62.5% condition. This meant that the push force had to be lower, or the ankle plantar flexors had to generate more force, before the net ankle moment could exceed the external moment caused by the ground reaction force and initiate foot rotation. Bobbert et al. (2002) found in a simulation study that foot rotation had to be delayed until the knee and hip joint moment decreased, allowing the resultant push force to drop.

Our results were consistent with this, showing no significant change in maximum ankle angular velocity and push duration, but a significant increase in ankle energy of 3.70 joules with anterior shifting of the PP from the 55% to the 62.5% condition. This is an indication of untapped muscular potential in the plantar flexors at the posterior position. Beyond the 62.5% condition, ankle energy only increased by 1.5 joules, with an accompanying significant decrease in maximum ankle angular velocity and increase in push duration. This result indicated a delayed onset of foot rotation, probably caused by insufficient plantar flexion strength, as was found in the simulation study (Bobbert et al., 2002).

It was shown in the literature (Houdijk et al., 2002) and in this study (Figure 6) that anterior shifting of the PP results in an increased knee flexion moment while the foot is rotating during the push phase. The accompanying larger range of knee joint motion and higher angular velocity causes an even greater absorption of knee joint energy. The data shows that the knee flexion moment and the accompanying push energy absorption at the knee joint are inevitable at the end of the push phase. To minimize the energy absorption, the PP must be shifted posteriorly, but then the ankle extensors are not maximally utilized. Theoretically, the optimal PP is at the position where the ankle extensors are maximally contracted and the onset of foot rotation is not delayed.

The secondary purpose of this study was to determine whether there is a relationship between a speed skater’s ankle plantar flexion capacity to generate torque and his or her optimal PP. No correlations were found. This suggests that plantar
Figure 6 — Joint moments and joint powers during the explosive push phase for the 4 pivot point conditions: 55%, 62.5%, 70%, 77.5%. End of push is marked by a vertical arrow with the shade corresponding to the condition. Push start is at time equal to zero. The data are averaged for one representative participant.

Flexor capacity to generate torque is not related to the optimal PP. The lack of significant correlations with respect to the static torque measures might be explained by the fact that the speed skating push is a dynamic movement. A maximal static torque measurement may not be close enough to the dynamic torques generated during the explosive movement. However, the optimal PP position may be independent of both the static and dynamic torque capabilities of the skater.

As mentioned earlier, a few studies have tried to quantify one optimal PP position for all speed skaters. Not only did they not find that spot but they also
failed to establish a range of pivot points within which all skaters would find their optimum (Allinger & Motl, 2000; Bobbert et al., 2002; Houdijk et al., 1999; 2002). This study found that 81% of the participants produced the most TE within the 55–62.5% range, indicating that this could be an optimal range of pivot points for most competitive skaters. It was reassuring to find no skaters producing maximal TE at the 77.5% condition, signifying an upper limit to the optimal PP range. Due to limitations with the positioning of the front mounting plate on the speed skate boot, it is impossible to modify a klap mechanism to allow for the PP to be placed any farther back (posterior) than what was used in the current study. However, with the large number of participants who produced more TE at the 55% position \((n = 6)\), it is likely that the optimal range extends posterior to that point.

In summary, one of the most useful findings of this study is that of a specific upper limit to the optimal PP placement range. At the 77.5% condition, no individual skater had his highest push energy. Also, some skaters may benefit from an even more posterior position than the 55% condition, bringing the PP closer to the actual physiological PP (metatarsal phalangeal joint). Findings like these should be considered when developing new klap mechanisms.

Acknowledgments

This study received financial support from the Medical Commission of the International Olympic Committee and Pfizer, Inc. The authors graciously acknowledge The Natural Science and Engineering Council of Canada for their funding.

References


