Influence of figure skating skates on vertical jumping performance

Marianne Haguenauer*, Pierre Legreneur, Karine M. Monteil

Centre de Recherche et d’Innovation sur le Sport, Université Claude Bernard - Lyon 1, 27-29, Bd du 11 Novembre 1918, 69 622 Villeurbanne Cedex, France

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Abstract

The purpose of this study was to investigate the influence of wearing figure skating skates on vertical jump performance and interjoint co-ordinations described in terms of sequencing and timing of joint rotations. Ten national to international figure skaters were filmed while performing a squat jump (SJ) on a force platform. Three experimental conditions were successively realized: barefoot (BF), lifting a 1.5 kg weight (LW) corresponding to the skates’ mass, attached on the distal extremity of each leg and wearing skates (SK). Jump height, angular kinematics as well as joints kinetics were calculated. Relative to the SJ height reached in the BF condition, SJ performance was significantly decreased by 2.1 and 5.5 cm in the LW and SK conditions, respectively. The restriction of ankle amplitude imposed by wearing skates was found to significantly limit the knee joint amplitude while the hip angular motion was not affected. Neither the skates’ mass nor the limited ankle angular motion modified the proximo-distal organization of joint co-ordination observed when jumping barefoot. However, with plantar flexion restriction, the delay between hip and knee extensions increased while it was reduced between knee and ankle extensions. Work output at the knee and ankle joints were significantly lowered when wearing skates. The decrease of work at the knee was shown to result from an early flexing moment causing a premature deceleration of the knee and from a reduction of knee amplitude. Taken together, these results show a minimization of the participation of the knee when plantar flexion is limited. It was proposed that constraining the distal joint causes a reorganization of interjoint co-ordinations and a redistribution of the energy produced by knee extensors to the hip and ankle joints.

Keywords: Added mass; Ankle restriction; Interjoint co-ordination; Squat jump

1. Introduction

Vertical jumping performance is related to the ability of the subject to generate work during the push-off and to transform this work into energy contributing to jump height (Bobbert and van Ingen Schenau, 1988). Many researches have shown that achieving a maximal performance depends on co-ordination, a proper sequencing and timing of joint movement (Hudson, 1986). Indeed, body segments contribute in a proximo-distal sequence to the acceleration of the CG (Bobbert and van Ingen Schenau, 1988; de Boer et al., 1987; Gregoire et al., 1984; Jacobs and van Ingen Schenau, 1992). When planning and executing a vertical jump, the motor system must take account of several constraints that are related to the motion of a complex neuro-musculoskeletal system in a gravitational field. Thus considering the properties of the musculoskeletal system, this sequential pattern of co-ordination is seen as the optimal pattern in the reach of maximum height of the CG during flight (Bobbert and van Soest, 2001).

Among these constraints, van Ingen Schenau (1989) has demonstrated that the proximo-distal delay of lower limb joint extensions is determined by the so-called geometrical and anatomical constraints. In vertical
jumping, the push-off is characterized by the explosive extension of the knee joint. The more the knee approaches its maximal extension, the less the transformation of the segment angular velocities into linear velocity of the CG is effective (geometrical constraint). Moreover, in order to preserve this joint from any damage, it is necessary to decelerate knee opening before its maximum extension (anatomical constraint). Bobbert and van Ingen Schenau (1988) have shown that the sequential order of the extension of the hip, knee and ankle joints delays the negative influence of the anatomical and geometrical constraints to the very end of the push-off. Particularly, the ankle joint allows for a further acceleration of the CG. Plantar flexion indeed plays a major role in a squat jump (SJ) performance. For instance, in an experimental simulation study, Luhtanen and Komi (1978) compared the takeoff velocity of a maximal SJ with the takeoff velocity attained in a maximal extension of the ankle joint while the knee was fixed at 180° during the whole push-off phase. These authors concluded that plantar flexion could theoretically contribute up to 22% to the takeoff velocity in a maximal SJ.

In figure skating, the range of motion of the ankle joint is strongly constrained by a stiff skate boot rigidly fixed to the blade. From the study of a ski jumping takeoff simulated in laboratory conditions, Virmavirta and Komi (2001) have shown that the ski jumping boot limits the contribution of plantar flexors. In addition, similarly to speed skaters, figure skaters learn from the early development of specific skills, i.e. jumping, to limit plantar flexion in order to prevent the front of the blade from scratching through the ice. In comparing a speed skating push-off performed with conventional speed skating skates and klaspers, (i.e. the latter allows the foot to rotate independently from the blade and moves the location of the foot’s center of rotation from the tip of the long blade, as in conventional speed skating skates, to under the ball of the foot), it has been concluded that klaspers enhanced the work output at the knee joint while no differences in ankle amplitude or the concurrent velocity of the CG. The CG velocity was calculated by integrating with respect to time the vertical mechanical power was calculated as GRF times the percentage of the body weight. Maximal instantaneous power was calculated as GRF times the concurrent velocity of the CG. The CG velocity was calculated by integrating with respect to time the vertical acceleration of the body’s mass center.

The objective of this study was to examine the modifications induced by wearing figure skating skates on a SJ performance through a kinetic and kinematic analysis. For this purpose, a single maximal SJ was performed in three testing conditions in order to differentiate the skates’ mass effects from those attributable to the limited action of the ankle joint. Particular attention will be paid to their effects on the vertical ground reaction force–time relation, the sequential order and timing of joint rotations and on joint kinetics.

2. Methods

Ten national to international figure skaters (age = 15.7±1.9 years; height = 1.66±0.08 m; body mass = 57.90±8.01 kg) gave their full informed consent to participate in this study. The population was composed of six female and four male subjects.

Prior to the experimental protocol, landmarks were placed on the left fifth metatarsophalangeal, lateral malleolus, lateral femoral epicondyle, greater trochanter and acromion. Then, a 10 min warm-up session and a few training jumps were realized in order to familiarize subjects with the task and to minimize possible bias that could be due to a lack of stability or to a not-adapted control. Subsequently, each skater performed three maximal SJs from an initial knee angle position of 90°. They were asked to jump as high as possible without downward movement while keeping their hands on their hips. These jumps were successively realized in three experimental conditions: (i) barefoot (BF), (ii) lifting a 1.5 kg weight corresponding to the skates’ mass, attached on the distal extremity of each lower leg (LW) and (iii) wearing skates (SK). For each condition of test, the best of the three trials, based on the maximum height reached during flight, was selected for further analysis. Thus, three vertical jumps were analyzed for each subject.

All the testing was done on an AMTI force plate model OR6-7-2000. The acquisition rate was set at 600 Hz. Data were acquired and processed using “Biosoft” software to determine the vertical component and the point of application of the ground reaction force (GRF) vector. The maximal vertical GRF value (Rzmax) and the absolute time between the start of the push-off and Rzmax were determined. Rzmax will be expressed as a percentage of the body weight. Maximal instantaneous mechanical power was calculated as GRF times the concurrent velocity of the CG. The CG velocity was calculated by integrating with respect to time the vertical acceleration of the body’s mass center.

Subjects were simultaneously filmed in the sagittal plane with a 60 Hz camcorder fixed on a tripod. The angle between the optical axis of the camcorder and the plane of movement was 90°. Distance between the
subject standing in the center of the force plate and the camera was 4.34 m. A vertical reference was placed in the plane of motion and filmed for the purpose of scaling.

Video images were digitized frame by frame using a specific self-developed motion analyzer. A four rigid segments model (foot, shank, thigh and upper body, i.e. head, arms and trunk: HAT) was obtained from the digitization of the landmarks’ center. The jump height \( H_{\text{max}} \) was calculated from the difference between the height of the CG at the apex of the jump and its height when the subject was standing upright with heels on the ground. Absolute co-ordinates of the landmarks were differentiated as a function of time to yield velocities of the landmarks. Joint angles were defined as shown in Fig. 1.

Joint co-ordination was evaluated through the sequential order and the timing of joint extensions. In this study, the instant of initiation of joint extension was detected when the joint angular position was 5% greater than its angular position at the start of the push-off. A proximo-distal sequence was identified when the hip started to extend before the knee whose extension preceded the ankle joint extension.

For each subject, kinetic and kinematic data were synchronized at the instant of takeoff (when Rz dropped to zero and the first video frame recorded on which the toes left the force plate) and truncated at the instant the CG vertical velocity was equal to zero.

Moreover, net intersegmental forces and joint moments were calculated using a standard inverse-dynamic procedure from the calculation of the point of application of the ground reaction force vector, linear and angular acceleration of segments, segmental moments of inertia, the location of joint centers and the product of net joint moment and joint angular velocity. Hip, knee and ankle work was obtained by integrating joint power over time.

The statistical analysis was performed on absolute data. To compare parameters between the three jump conditions, the non-parametric Friedman test and Wilcoxon signed-rank test were successively used for statistical analysis. In order to present average curves, data were normalized using a spline cubic interpolation method (de Boor, 1978). For better readability and to clearly identify the skates’ mass and the plantar flexion restriction effects, we will present statistical differences between the BF and LW conditions and between LW and SK conditions. Statistical significance was accepted at the \( p < 0.05 \) level.

3. Results

This section will focus on kinetic and kinematic modifications induced by wearing skates. Results will be presented in order to differentiate the skates’ mass and the restrictive ankle extension effects.

First of all, in order to validate the testing procedures, we examined the subjects’ initial position during the push-off phase of the jump. Initial hip, knee and ankle angles were similar between the three conditions of test (Table 1). Therefore, the prerequisite was satisfactorily fulfilled and allowed for comparison.

When compared to BF condition (Table 2), adding a mass on the distal extremity of the shanks (LW) significantly decreased the SJ performance by on average 2.1 cm \( (p = 0.022) \). Wearing skate (SK) further reduced jump performance by on average 3.4 cm \( (p = 0.005) \) (Table 2).

Table 1

| Mean and standard deviation values of initial angles \( (t = 0) \), takeoff angles and amplitude of the hip, knee and ankle for the BF, LW and SK conditions |
|---|---|---|
| BF | LW | SK |
| At \( t = 0 \) | | |
| \( \theta_{\text{H}} \) (rad) | 1.55±0.19 | 1.43±0.26 | 1.43±0.28 |
| \( \theta_{\text{K}} \) (rad) | 1.85±0.09 | 1.81±0.15 | 1.89±0.14 |
| \( \theta_{\text{A}} \) (rad) | 1.69±0.11 | 1.72±0.09 | 1.65±0.11 |
| At takeoff | | | |
| \( \theta_{\text{H}} \) (rad) | 2.93±0.14 | 3.01±0.12 | 2.95±0.13 |
| \( \theta_{\text{K}} \) (rad) | 3.01±0.15 | 3.03±0.13 | 2.87±0.13† |
| \( \theta_{\text{A}} \) (rad) | 2.41±0.22 | 2.43±0.17 | 2.14±0.11†† |
| Amplitude | | | |
| \( \theta_{\text{H}} \) (rad) | 1.38±0.23 | 1.58±0.25 | 1.51±0.23 |
| \( \theta_{\text{K}} \) (rad) | 1.15±0.21 | 1.23±0.2 | 1.08±0.11† |
| \( \theta_{\text{A}} \) (rad) | 0.72±0.26 | 0.71±0.19 | 0.49±0.16†† |

†\( p < 0.05 \) SK vs. LW.
††\( p < 0.01 \) SK vs. LW.
Peak vertical GRF values were similar for the three conditions (see Table 2 and Fig. 2). The peak mechanical power was significantly decreased when the jumps were performed in SK only. Vertical GRF patterns differed during the rise of GRF and more especially, the initial slope was greater when subjects jumped barefoot than in LW and SK conditions (Fig. 2).

This trend was confirmed through statistical analysis of the absolute time to reach maximal vertical GRF value. This latter was significantly increased by the added mass (BF: $0.246 \pm 0.06$ s; LW: $0.326 \pm 0.11$ s; SK: $0.301 \pm 0.08$ s; LW vs. BF, $p = 0.037$; SK vs. LW, $p = 0.285$). However, no significant difference of the total push-off phase duration could be shown between the three conditions (Table 2).

We will now attempt to gain further insight of the differences previously evoked by considering the sequencing and timing of joint extensions.

Representative curves of hip, knee and ankle joint angle over the SJ push-off for the three conditions of test are presented in Fig. 4. With regards to the sequential order of joint extensions, it was found that the hip, knee and ankle extended successively, following a proximo-distal sequence for each jump condition. The added mass neither altered the instant of joint extensions in the push-off nor the instant of knee and ankle extension relative to their proximal joint extension, respectively (Fig. 3). The comparison of lower limb joint extension instants showed that knee extension was initiated later in the push-off when wearing skates (SK vs. LW, $p = 0.028$). Considering the interval time between hip and knee extension and between knee and ankle extension, statistical results pointed out that, when jumping with skates, knee opening occurred later relative to hip extension (SK vs. LW, $p = 0.031$) and

![Fig. 2. Vertical component of the ground reaction force (Rz) time-courses during squat jump (SJ) in the barefoot (BF), lifting weight (LW) and wearing skates (SK) conditions for one representative subject (left chart) and averaged between subjects (right chart). In the left chart, time is expressed in seconds (with $t = 0$, corresponding to takeoff) and Rz is expressed in Newtons. In the right chart, time is expressed as a percentage of the push-off phase duration (with $t = 100\%$, corresponding to takeoff) and Rz is expressed as a percentage of body weight.]

![Fig. 3. Mean and standard deviation values of the difference between the instant of knee extension and hip extension ($t_{K} - t_{H}$) and the difference between the instant of ankle extension and knee extension ($t_{A} - t_{K}$) for the barefoot (BF), lifting weight (LW) and wearing skates (SK) conditions. *$p < 0.05$.](https://example.com/fig3.png)
the delay between knee and ankle extensions is significantly reduced (SK vs. LW, \( p = 0.017 \)) (Fig. 3).

Maximal hip and knee angular velocities were not modified when lifting an added weight at the distal end of the shank (Table 2) but a significant decrease of ankle angular velocity was observed in that experimental condition. When jumping with skates, the hip angular velocity was not altered while the knee and ankle angular velocities were significantly lower than in the LW jump. Concerning the final position of the subject at takeoff, no significant difference was found between BF and LW conditions (Table 1). When wearing skates, hip angle remained unchanged. Only knee and ankle angles at takeoff were significantly reduced in SK jump (Table 1). The knee and ankle amplitudes calculated from the difference between the final and initial angles were found to be significantly decreased by 0.15 ± 0.1 and 0.22 ± 0.2 rad on average respectively when wearing skates (Table 1).

Mean times histories of net moment at the hip, knee, ankle joints and net joint power for the BF, LW and SK conditions are also presented in Fig. 4. Peak hip moment and peak hip power were not found different between the three jump conditions (Table 3 and Fig. 4). The peak moment at the knee was significantly reduced \( (p = 0.013) \) in LW. However, no significant difference was

<table>
<thead>
<tr>
<th>Peak positive moment (N.m)</th>
<th>BF</th>
<th>LW</th>
<th>SK</th>
</tr>
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<tbody>
<tr>
<td>Hip</td>
<td>327.6 ± 51.4</td>
<td>282.9 ± 75.4</td>
<td>274.8 ± 62.8</td>
</tr>
<tr>
<td>Knee</td>
<td>183.9 ± 48.0</td>
<td>124.5 ± 33.6*</td>
<td>100.7 ± 48.3†</td>
</tr>
<tr>
<td>Ankle</td>
<td>294.4 ± 64.4</td>
<td>266.5 ± 63.2*</td>
<td>309.8 ± 71.9††</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Work (J)</th>
<th>BF</th>
<th>LW</th>
<th>SK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip</td>
<td>206.3 ± 26.5</td>
<td>198.5 ± 36.3</td>
<td>248.1 ± 52.1</td>
</tr>
<tr>
<td>Knee</td>
<td>91.8 ± 16.4</td>
<td>105.5 ± 30.2</td>
<td>57.6 ± 18.8††</td>
</tr>
<tr>
<td>Ankle</td>
<td>191.9 ± 44.7</td>
<td>166.8 ± 62.5</td>
<td>124.9 ± 33.8††</td>
</tr>
<tr>
<td>Total</td>
<td>490.1 ± 79.7</td>
<td>470.8 ± 48.6</td>
<td>430.6 ± 86.7††</td>
</tr>
</tbody>
</table>

\*\( p<0.05\) LW vs. BF, \( ^{†} p<0.05 \) SK vs. LW, \( ^{††} p<0.01 \) SK vs. LW.

Fig. 4. Time histories of ankle, knee and hip angles, moment, and power output during SJ push-off phase for the skaters in the BF (top charts), LW (middle charts) and SK (bottom charts) conditions (\( t = 100\% \), corresponding to takeoff).
found between the BF and LW conditions for the peak knee power. The peak positive moment and power developed at the ankle joint was lowered in the LW jump ($p<0.028$). In the SK condition, the peak knee moment and power were significantly reduced (Table 3 and Fig. 4). When jumping with skates, participants produced a greater peak moment at the ankle ($p=0.005$) but the peak power developed at this joint was significantly decreased ($p=0.037$). No significant difference in maximal flexing moment values at the joints was found between the three experimental conditions. However, the moment and power developed at the knee started to be negative significantly earlier in the SK condition than in LW (BF vs. LW, $p=0.061$; SK vs. LW, $p=0.023$) (Fig. 4).

Although the mean total work was 19.3 J lower in LW than in BF, this difference was not found significant between these two conditions (Table 3). When compared to LW, the total work was significantly reduced by 40.2 J when wearing skates ($p=0.037$). Although no difference in hip work existed between the three jumping conditions, this parameter was on average 49.6 J greater when wearing skates than in LW. The work produced at the knee and ankle joints was significantly reduced by on average 67.9 and 41.9 J, respectively, by the restriction of plantar flexion ($p<0.009$).

4. Discussion

This study was aimed at determining the influence of wearing figure skating skates on a SJ performance through the analysis of joint kinematics and kinetics. We will first validate the barefoot condition by comparing the present results with the literature. Then, the influence of the skates’ mass and of the limited plantar flexion on relevant parameters that characterize a maximal SJ performance will be discussed.

Push-off times obtained in the barefoot condition (357 ± 42 ms) are in agreement with the literature reporting a push-off phase duration ranging from 300 ms to 360 ms (Bobbert and van Ingen Schenau, 1988; Gregoire et al., 1984; Jacobs et al., 1996). Regarding kinetic parameters, the peak ground reaction forces reached 2.3 (±0.2) times body weight. This value is in accordance with the results obtained in a previous study (Pandy and Zajac, 1991) that reported a peak value of 2.2 times body weight on average during a SJ push-off. When looking at angular parameters characterizing subjects position at takeoff, hip, knee and ankle joints angles differed by less than 0.1 rad from Bobbert and van Ingen Schenau (1988). Therefore, the barefoot SJ data of the present study agreed with literature. This condition being validated, the effects of both skates’ mass and plantar flexion restriction will now be successively examined.

Results pointed out that the addition of an external load on the distal extremity of the shanks impaired SJ performance. More especially, skates’ mass decreases jump height by 2.1 cm. When looking at the difference in jump height between the jumps performed barefoot and with an added mass, it appears that the amount of decrease of performance is only explained by the value of the added mass in itself, i.e. potential energy at the apex of the flight is equivalent between BF and LW (average values of 168.1 and 168.3 J for BF and LW, respectively). Although a difference in total work calculated from inverse dynamics existed between BF and LW, it was not found to be significant. In BF and LW conditions, skaters produced the same amount of work but on different masses, which explains the difference in jump performance between these two conditions. The difference in work done across the individual joints may be explained by inaccuracy of calculations due to the high sensitivity of output data to input data and more particularly to joint angular accelerations when using a standard inverse dynamics computations (Cahouët et al., 2002). Neither angular positions (Fig. 4) nor the interjoint co-ordination pattern (Fig. 3) were altered by the mass of the skates. Indeed, the proximo-distal sequence of the joint extensions commonly observed in unconstrained vertical jump (e.g. Bobbert and van Ingen Schenau, 1988) and the delay between lower limb joint extensions were not changed by the added mass.

In order to solely take into account the influence of the plantar flexion restriction, differences between the added weights and wearing skates conditions were considered. In addition to the decrease of jump height induced by the skates’ mass, wearing figure skating skates causes an additional loss of 3.4 cm. Based on the results coming from the inverse dynamics, it appears that the decrease of jump performance when wearing skates results from a reduction of work output at the knee and ankle joints. The work done at the hip was not significantly different between the jump conditions although it tended to increase when wearing skates.

The difference of work output at the ankle between the three jump conditions occurred at the very end of the push-off (Fig. 5), that is, when approaching the takeoff ankle angle, which was found to be significantly lower than in the unconstrained jump. The ankle moment started to largely drop beyond an ankle angle of 1.9 rad. Results showed that peak ankle extension moment is increased in SK. Due to the force–velocity relationship of skeletal muscles, the decreasing ankle angular velocity observed in the present experiment increases the ability of plantar flexors to generate a larger force. Hence, the decrease of work output at the ankle seems to be mainly attributable to the limited ankle range of motion, which limits the range of shortening of plantar flexors. In contrast to the present study, research work that
compared skating with conventional speed skates and klapskates found similar ankle amplitude between these two types of skates (Houdijk et al., 2000). Consequently, work produced by plantar flexors was not increased with klapskates. However, klapskates were shown to increase the work output at the knee. The differences in speed skating push-off mechanics were attributed to the modification of the location of the foot’s center of rotation. It is reasonable to establish a correspondence between the present testing conditions (LW vs. SK) and experimental or simulation studies in which the effects of the location of the foot’s center of rotation on the mechanics of a speed skating push-off or a one-legged vertical jump were examined. In both cases, the foot’s center of rotation was indeed moved from the metatarsophalangeal joint (BF, LW and klapskates) to the tip of the blade (SK condition and conventional speed skating skates). However, many of the present results differ from those observed in studies that examined the influence of shifting the foot’s center of rotation to the anterior of the metatarsophalangeal joint. In a simulation study, Houdijk et al. (2003) have demonstrated that increasing the distance between ankle and foot’s center of rotation above a certain length could result in an increase of shortening velocity of plantar flexors. Present findings are not in agreement with the study of Houdijk et al. (2003). It seems therefore that the modification of the foot’s center of rotation when jumping with figure skating skates exerted little influence on the push-off performance compared to the plantar flexion restriction effect. We believe therefore that the shape of the figure skating boot, which limits plantar flexion, induces a decrease of work at the ankle.

The present experiment shows a significant decrease of both ankle and knee angular amplitude when jumping with figure skating skates. These reduced amplitudes seem to be attributable to the restricting structure of the figure skating skates and not to the modification of the foot’s center of rotation. Indeed, Allinger and Motl (2000) found similar lower limb joints amplitude when moving the foot’s center of rotation forward in a vertical jump task while Houdijk et al. (2002) even reported larger hip and knee amplitudes in a speed skating push-off. Contrary to the study conducted on vertical jumps with ski jumping boots (Virmavirta and Komi, 2001), the hip position at takeoff was not modified in the present study. Regarding ankle angular limitation, it seems that ski jumping boots are more restrictive than figure skating. From similar initial ankle angles, Virmavirta and Komi (2001) indeed found a decrease of ankle amplitude of 0.40 rad with ski jumping boots while it was reduced to a lower extent with figure skating skates (0.23 rad). This suggests that there may be an angular threshold of ankle restriction beyond which hip final position is modified.

The reduction of work output at the knee is in agreement with some observations made in studies where the location of the foot’s center of rotation was shifted anteriorly (Houdijk et al., 2000, 2002, 2003). However, another protocol failed to show any difference in joint work output when performing a one-legged maximal jump on different length rigid boards (Allinger and Motl, 2000). In experiments where an effect was observed, this decrease of work at the knee was attributed to an increased contraction velocity of knee extensors (Houdijk et al., 2002, 2003) and to a greater knee flexing moment (Houdijk et al., 2002). The present findings show a reduction of knee angular velocity when wearing skates. The decrease of work at the knee seems therefore to be explained by a shift in the onset of knee flexing moment, which occurred at a smaller knee angle than in BF and LW and a reduced range of motion of that joint with plantar flexion restriction (Fig. 5). It was indeed found that the net moment at the knee becomes negative earlier in the push-off when jumping with skates than in the LW and BF jumps. When considered

![Fig. 5. Average angle-moment curves for the hip, knee and ankle joints during SJ in BF (thick solid line), LW (grey dotted line) and SK (thin solid line) conditions.](image-url)
together with the timing of joint extensions, results tend to show a minimization of the participation of the knee. Although the sequential nature of interjoint co-ordinations was not altered with skates, our findings revealed that the timing of joint extensions is modified when jumping with skates. Knee opening was found to be delayed relative to the start of hip extension. Hence, compared to the unconstrained jump, the knee starts to extend later and decelerates earlier when wearing skates. The shift in the onset of negative net moment at the knee may be due to either an early decrease in moments of knee extensors or an early moment of flexors. We believe that results related to the timing of joint rotations provide indications that the second hypothesis takes precedence over the first one. Indeed, it was found that the time elapsed between knee and ankle extensions is decreased when jumping with skates. The observed changes of timing of joint extensions seem to come from the limitation of plantar flexion by the skate boot and not from the modification of the location of the foot’s center of rotation. Indeed, moving the foot’s center of rotation anteriorly either did not affect the timing of joint extensions (Allinger and Motl, 2000; Houdijk et al., 2000) or delayed the rotation of the foot segment (Bobbert et al., 2002; Houdijk et al., 2002, 2003). In the present experiment, a further analysis revealed that the interval time between shank and foot rotation tended to be smaller in SK than in LW and BF. This shows that the net ankle moment was increased sufficiently early in the push-off to exceed the large ground reaction force moment when jumping with skates (longer lever arm). Therefore, the early decrease of flexing moment and the early extension of the ankle likely results from an early activation of the biarticular gastrocnemius. We hypothesize that the control strategy is modified in relation to mechanical modifications induced by wearing figure skating skates, i.e. limited ankle range of motion and, to a lower extent, anterior position of foot’s center of rotation. Nevertheless, the first hypothesis cannot be firmly ruled out and a further study that will assess muscle activation patterns (onset time, offset time and amplitude) using electromyographic recordings will be necessary to verify our hypothesis.

The early negative moment at the knee shows that the knee joint absorbs work to a greater extent at the end of the push-off when jumping with skates than in LW and BF jumps (Fig. 5). Results revealed that the greater work at the hip is not due to a larger shortening distance of hip extensors in SK than in LW. The increased hip work could be rather ascribed to a greater capacity of biarticular hamstrings muscles to transport the energy produced by knee extensors to the hip when jumping with skates as discussed by Houdijk et al. (2002). It is also likely that part of the energy produced at the knee is transported to the ankle joints via gastrocnemius muscles. It is interesting to note that the knee kinetics are already rather low in the reference condition, that is, the barefoot jump compared to the literature while the hip and ankle kinetics are analogous to values reported in previous studies (e.g. Aragón-Vargas and Gross, 1997). This low value could be a characteristic of the tested participants and may be seen as an adaptation related to their activity.

In conclusion, jumping with skates resulted in an important decrease of performance that can be attributed to the mass of the skates as well as the limited plantar flexion. The present study tends to demonstrate that figure skaters could take advantage of a mass reduction of the skates. Moreover, constraining the range of motion of the distal joint was shown to affect its adjacent joint only. Such a constraint causes a reorganization of the system in terms of joint co-ordinations and of work production at the ankle and knee joints in highly skilled figure skaters. This particular organization seems to prove that constraining one joint causes a redistribution of the energy produced by knee extensors to the hip and ankle joints.

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