Leg stiffness and joint stiffness while running to and jumping over an obstacle

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ABSTRACT

1. Introduction

During running, the muscles–tendons units of the lower limb act like a linear spring storing and releasing elastic energy during contact (Alexander, 1992; Blickhan, 1989; Cavagna et al., 1988; McMahon and Cheng, 1990). When the running conditions are changing, the bouncing mechanism is adapted by adjusting the stiffness of the leg-spring system (k_{leg}) and the angle swept during contact. When the speed of progression increases, k_{leg} does not change but the angle swept increases (Farley et al., 1993; He et al., 1991; Morin et al., 2005). If at a given speed the step frequency is increased, k_{leg} increases and the angle swept decreases (Farley and Gonzalez, 1996); k_{leg} is also adapted when subjects are running on an uneven ground (Seyfarth et al., 2002; Grimmer et al., 2008) or when the softness of the surface is modified (Ferris et al., 1999, 1998).

Mauroy et al. (2012) have shown that when approaching an obstacle, k_{leg} and the angle swept are adjusted during the last two contacts before the jump. Two contacts before the obstacle, k_{leg} decreases whereas the angle swept increases slightly, and the COM is lowered and accelerated forwards. Then, during the last contact before the obstacle, k_{leg} increases whereas the angle swept decreases, and the COM is raised and accelerated upwards, while its forward velocity decreases.

During running and hopping on place, the lower limb can be assimilated to a multi-jointed system composed of 4 segments – foot, shank, thigh, head–arms–trunk – and 3 torsional springs – ankle, knee, hip (Fig. 1). The overall leg-spring stiffness, k_{leg} depends (1) on the torsional stiffness, k_{t}, of the joints and (2) on the geometry of the leg at touchdown (Farley et al., 1998; Farley and Morgenroth, 1999). Torsional stiffness of a joint is defined as the slope of the relation between the net muscular moment (M) and the angular displacement at that joint (Stefanyshyn and Nigg, 1998); k_{t} determines how much the joint angle changes in response to a given external moment. It depends on muscle activation, reflexes and joint angle (Agarwal and Gottlieb, 1977; Gottlieb and Agarwal, 1978; Hunter and Kearney, 1982; Nielsen et al., 1994; Sinkjaer et al., 1988; Weiss et al., 1988; Weiss et al., 1986a,b). If the lower limb joints are stiffer, they undergo smaller angular displacements during contact, resulting in less leg compression and higher leg-stiffness.

A second factor influencing k_{leg} is the touchdown leg geometry (Farley et al., 1998; Farley and Morgenroth, 1999), i.e. the position of the joints relative to the ground force vector when landing. For a given ground reaction force and a given k_{t}, if the joints are more flexed during contact, the lever arms and thus the net external
The role of each of the joints in the modulation of the joint torsional stiffness at the ankle, the knee and/or at the leg stiffness. Similarly, when humans run with exaggerated knee flexion, the net muscular moment and power (by the inverse dynamic method) and in the joint torsional stiffness at the level of the hip, knee and ankle during the steps preceding the jump over an obstacle.

2. Methods

In this section, the methods and experimental procedure are only explained shortly. A detailed description the experimental setup and procedure and of the data analysis is proposed as Supplementary material online.

2.1. Subjects and experimental set-up and procedure

Experiments were realized on eight young male recreational runners. Written informed consent was obtained. Experiments were performed according to the Declaration of Helsinki and approved by the local ethics committee.

Subjects ran at 15 km h^{-1}, jumped over a 0.65 m-high barrier and continued to move at the same pace. Ground reaction forces were recorded using a 13 m-long force platform (Geeni and McMahon, 2010). A barrier was mounted 3 m before the end of the force-platform.

Two pairs of photocells placed at each end of the plates on the level of the neck measured the average running velocity. Traces were analyzed if the average velocity of the first step(s) before the barrier ranged between 14.5 and 15.5 km h^{-1}. Steps were numbered as follows: step 0 corresponded to the last contact before the obstacle and the following aerial phase over the obstacle, step 1 was the step before step 0, etc. Control steps, i.e. runs without any obstacle, were also recorded.

Reflective markers were glued on the skin at the level of the lower limb joints. Their position in the sagittal plane was measured each 5 ms by a high-speed video camera (BASLER A501k). Movements of the supporting leg were recorded during contact (three trials on step 1, three on step 0, six on control steps). Camera and force-plates were triggered by the photocells. Coordinates of the reflectors were measured using a semi-automatic tracking software (Lynxzone, Arsalis).

2.2. Data analysis

Data processing was performed using custom software (LABVIEW 10.0, National Instruments). The leg was assimilated to a simple linear spring with the COM located at its upper end. This leg-spring system swept on an arc during the contact and the overall stiffness (k_{leg}) generated by the lower limb muscles was estimated by computer simulation (Mauroy et al., 2012). The kinetic, potential and total energy of the COM was computed using the method of Cavagna (1975).

The net muscular moment (M_i), power (P_j) and work (W_j) at the ankle, knee and hip were evaluated in the sagittal plane by an inverse dynamic method (Elliott, 1939). The M_i, P_j and W_j at each joint were computed on the limb in contact when F was greater than 10% of body weight. The net work (W_{net}) is the difference between the positive and negative work done during the contact at each joint. Throughout the text, the subscript j refers to any lower limb joint, the subscript a refers specifically to the ankle, b to the knee and h to the hip.

The torsional stiffness of each joint (k_j) was determined from the ratio of the change in net muscle moment to joint angular displacement in the sagittal plane (ΔM_j/Δθ_j) between the beginning of the ground contact phase and the instant when the joints were maximally flexed (Farley and Morgenroth, 1999; Kuitunen et al., 2002; Stefanishyn and Nigg, 1998).

Results were grouped in classes according to the step number (control step, step-1 and step 0). A one-way repeated measures ANOVA (Bonferroni post-hoc) was performed to evaluate the effect of the step number on the variables studied.

3. Results

3.1. Leg-stiffness and joint stiffness during steady-state running

During steady-state running, the leg-spring is bouncing and sweeping forward in a symmetric way. The magnitude of angle between the leg and vertical (θ_h) at touchdown and at takeoff are about equal, the distance between the hip and the fifth metatarsal...
(L) is minimal and the force exerted by the lower limb on the ground (F) is maximal when θ ≈ 0 (Fig. 2). The F–L relation is quasi-linear (Fig. 3) suggesting that the lower limb muscles act like a spring. The value of the overall stiffness k_{leg} (Table 1) is consistent with the one of McMahon and Cheng (1990) and of Mauroy et al. (2012).

The ankle presents a dorsiflexion during the first half of the contact phase and a plantar-flexion during the second half (Fig. 5). The net muscular moment (M_a) is in plantar-flexion during the greatest part of the contact phase; M_a increases during dorsiflexion (Fig. 3) and decreases during plantar-flexion. The M_a–θ_a relation is quasi-linear suggesting that the ankle muscles act like a torsional spring of stiffness k_a (Table 1). The surface under curve during dorsiflexion is smaller than the surface during plantar-flexion showing that the muscle-tendon units are performing more positive than negative work (Fig. 4) and W_{net,a} is positive (Table 1).

The knee flexes during the first ~40% of contact and extends during the last ~60% (Fig. 6). During most of contact, extensor muscles of the knee are contracting first eccentrically then concentrically. Knee muscles perform thus slightly more negative work than positive work (Figs. 4 and 6) and W_{net,h} is negative (Table 1). The M_h–θ_h relation is quasi-linear (Fig. 3), suggesting that knee muscles act like a torsional spring of stiffness k_h (Table 1).

At the level of the hip, M_h is an extension moment and presents a peak ~10% after touchdown (Fig. 7). During the first 20–30% of contact, hip movements are small and P_h is close to zero. Then the hip extends during the rest of the contact phase, however M_h and P_h are small. Hip muscles perform slightly more negative work than positive work (Figs. 4 and 7) and W_{net,h} is negative (Table 1). The M_h–θ_h curve does not present the classical “storage-release” relation of a torsional spring (Fig. 3).

3.2. Leg-stiffness and joint stiffness during step-1

During contact of step-1, the maximal F is smaller than during steady-state running (Fig. 2). Furthermore, the orientation of F (θ_h) becomes more vertical than the orientation of the lower-limb (θ_a) at the end of contact. The F–L relation is quasi-linear (Fig. 3); however, k_{leg} is reduced as compared to control steps (Table 1). Consequently, at takeoff, the leg is more horizontal than during control steps (Fig. 2). Due to the change in orientation (Mauroy et al., 2012), the COM is lowered and accelerated forward (Fig. 4). During this phase, due to the lowering of the COM, E_{tr} (Fig. 4) is reduced by 0.71 ± 0.13 J kg^{-1} (mean ± SD) whereas E_{fr} increases
from 0.69 ± 0.61 J kg⁻¹; as a consequence, \( W_{\text{net}} \) is close to zero (Table 1).

At the ankle, \( M_a \) is a plantar-flexion moment during the greatest part of contact (Fig. 5), however the maximal \( M_a \) and \( P_a \) are smaller than during control steps. The shape of the \( M_a-\theta_a \) curve is similar to control steps (Fig. 3), although \( k_a \) is smaller (Table 1). As compared to steady-state running, \( \theta_a \) at takeoff is smaller (Fig. 5).

At the knee, the shape of the \( M_k-\theta_k \) curve is similar to control steps (Fig. 3) although \( M_k \) and also \( P_k \) are smaller (Fig. 6). As compared to control steps, \( k_k \) is reduced (Table 1) whereas \( W_{\text{net,k}} \) is not different (Table 1). During the second part of contact, the knee stays in flexion (Fig. 6).

At the hip, the shape of the \( M_h-\theta_h \) curve is similar to control steps (Fig. 3), except at the end of contact where \( M_h \) is a flexion moment and where the negative \( P_h \) is greater (Fig. 7).

Consequently the balance between negative and positive work done increases (Table 1).

### 3.3. Leg-stiffness and joint stiffness during step 0

During step 0, the maximal \( F \) (Figs. 2 and 3) and \( k_{\text{leg}} \) (Table 1) are greater than during control steps. Furthermore, \( \theta_k \) becomes more horizontal than \( \theta_h \) at the end of contact. During this step, the COM is lifted and accelerated upwards while its forward velocity decreases (Fig. 4). The energy gained by enhancing the vertical movement of the COM is greater than the kinetic energy lost by decreasing the velocity of progression and \( W_{\text{net}} \) is greater than during control steps (Table 1). The energy saving mechanism during step 0 is similar to the one observed in pole vaulting (Mauroy et al., 2012).
Table 1

Upper part: overall leg-spring stiffness (k_leg) and torsional joint stiffness at the knee (k_k) and at the ankle (k_a) during running in steady state (control step), two contact periods before the jump over the obstacle (step-1) and during the contact period preceding the jump over the obstacle (step-0). Lower part: net external work (i.e. positive external work minus negative external work) done during contact (W_net) to move the COM relative to the surroundings and net muscular work (i.e. positive minus negative work) done during contact at the level of the hip (W_net,h), the knee (W_net,k) and the ankle (W_net,a) of control steps, step-1 and step-0. Numbers are the mean ± SD of all the traces (n=48 for control steps, n=24 for step-1, n=24 for step-0).

<table>
<thead>
<tr>
<th></th>
<th>Control step</th>
<th>Step-1</th>
<th>Step-0</th>
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<tbody>
<tr>
<td>Leg and joint stiffness</td>
<td></td>
<td></td>
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<tr>
<td>k_leg (kN m⁻¹ kg⁻¹)</td>
<td>0.18 ± 0.02</td>
<td>0.13 ± 0.01*</td>
<td>0.28 ± 0.04*</td>
</tr>
<tr>
<td>k_k (N m rad⁻¹ kg⁻¹)</td>
<td>8.46 ± 1.52</td>
<td>6.06 ± 1.15*</td>
<td>13.86 ± 5.71*</td>
</tr>
<tr>
<td>k_a (N m rad⁻¹ kg⁻¹)</td>
<td>11.54 ± 2.02</td>
<td>7.03 ± 1.63*</td>
<td>18.66 ± 3.47*</td>
</tr>
</tbody>
</table>

Mass-specific net work during contact

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<tr>
<td>W_net (J kg⁻¹)</td>
<td>−0.01 ± 0.06</td>
<td>−0.02 ± 0.56</td>
<td>1.02 ± 0.35*</td>
</tr>
<tr>
<td>W_net,h (J kg⁻¹)</td>
<td>−0.27 ± 0.24</td>
<td>−0.54 ± 0.34*</td>
<td>0.14 ± 0.28*</td>
</tr>
<tr>
<td>W_net,k (J kg⁻¹)</td>
<td>−0.27 ± 0.11</td>
<td>−0.31 ± 0.21</td>
<td>−0.21 ± 0.2</td>
</tr>
<tr>
<td>W_net,a (J kg⁻¹)</td>
<td>0.78 ± 0.16</td>
<td>0.40 ± 0.20*</td>
<td>0.84 ± 0.17</td>
</tr>
</tbody>
</table>

* indicates that a significant difference was found between control steps and steps-1 or between control steps and step-0.

As in control steps and step-1, M_a is generated by the plantar-flexor muscles during the greatest part of contact (Fig. 5), however the maximal M_a and P_a are greater. The θ_a-time curve is shifted towards a greater plantar flexion. The slope of the M_a-θ_a curve (Fig. 3) is steeper showing that the stiffness k_a is greater than during steady-state running (Table 1). During the first part of contact, the muscular moment in plantar flexion increases while the joint is performing a dorsiflexion, muscles are thus realising an eccentric contraction. During the second part of contact, the muscular moment in plantar flexion decreases while the joint is performing a plantar flexion; muscles are thus realising a concentric contraction. The surface under the M_a-θ_a curve represents the work done by the muscles; this surface is smaller during the eccentric phase than during the concentric phase. Consequently, W_net,a is positive but not greater than during control steps (Table 1).

At the knee, M_k is a flexion moment at the beginning and at the end of contact of step 0 (Fig. 6). During the rest of the contact, M_k is an extension moment. The maximum of M_k and the maximal positive P_k are not statistically different than during control steps (see numbers in Fig. 6). Knee extensor muscles perform more
negative than positive work (Figs. 3 and 4) and $W_{\text{net,k}}$ is negative (Table 1). The shape of $M_k-\theta_k$ curve is similar than in control steps although $k_k$ is greater (Table 1).

At the level of the hip, $M_h$ is an extension moment during most of contact (Fig. 7). As compared to control steps, $M_h$ is greater, however $P_h$ remains small. $W_{\text{net,h}}$ is positive (Table 1), showing
that extensor muscles are doing positive work to increase hip extension and lift the COM at the end of contact.

4. Discussion

When a runner prepares to cross an obstacle, \( k_{\text{leg}} \) is modified during the two steps preceding the jump: \( k_{\text{leg}} \) is first decreased then increased to verticalize the direction and amplify the magnitude of the velocity vector at takeoff (Mauroy et al., 2012). This last observation confirms the hypothesis of Farley et al. (1998) that, when running in nature at given speed, the leg-spring stiffness is modified to change direction or to leap an obstacle.

To analyze the influence of the torsional stiffness and of the lower limb geometry on \( k_{\text{leg}} \), we evaluated the net muscular moment and the angular displacement at the level of the hip, knee and ankle during the steps preceding a jump. The results obtained at the level of the ankle and the knee during steady-state running, are in good agreement with those found in the literature (Arampatzis et al., 1999; Gunther and Blickhan, 2002).

Note that in our model, we assume that movement and muscle actions occur in the sagittal plane. However, Glitsch and Baumann (1997) and McClay and Manal (1999) highlighted the potential importance of non-sagittal plane dynamics during running and thus the work done at each is joint as estimated in our study is most likely underestimated.

4.1. Torsional springs during steady-state running

At the level of the knee, the \( M_{\text{k}}-\theta_{\text{k}} \) curve presents the classical shape of a torsional spring (Fig. 3). However, the resilience of the spring is less than 100%, since the negative work is smaller than the amount of positive work done during contact.

Ankle muscles also act like a torsional spring. However, contrary to the knee muscles, ankle muscles do more positive than negative work (Figs. 3 and 4). Supposing a resilience of 100%, the surface between the two lines on the \( M_{\text{a}}-\theta_{\text{a}} \) curve represents the additional positive work done by ankle during contact (Table 1).

At the level of the hip, the \( M_{\text{h}}-\theta_{\text{h}} \) curve does not behave like a torsional spring. During the first 30% of contact, extensor muscles perform an isometric contraction to stabilize the hip during loading. Indeed, the leg-spring is in front of the COM and the \( F \) vector is oriented more vertically than the leg-spring (Fig. 7). As a consequence, hip extensor muscles are developing an important moment to counterbalance the action of \( F \) (Fig. 7). During the last 70% of contact, \( F \) and the leg-spring are more or less oriented in the same direction. So the net muscular moment and power are small suggesting that hip extends rather passively, when the leg-spring is sweeping forwards.

4.2. Influence of the segment masses on the net muscular moment

The influence of the segment masses on the computation of \( M_{\text{i}} \) increases from distal to proximal (Gunther and Blickhan, 2002). At the level of the ankle and the knee, the moment generated at the joints by the ground reaction force \( F \) (dotted line in the left panel of Figs. 5, 6 and 7) is close to the net muscular moment \( M_{\text{i}} \), showing that the inertial effect (both in translation and in rotation) of the limb segments can be neglected in the estimation of the net muscular moment. At the level of the hip, the inertial effect is not negligible, although the dynamic deviations are small.
moment in extension (or plantar flexion), which generates a muscular moment in (dorsi-)flexion, which generates a moment in (dorsi-)flexion. Others indications are as in Fig. 2.

4.3. Work balance at the joint

During steady-state running and during step-1, the net external work done each step is nil (Fig. 4). However, it is peculiar to observe that \( W_{\text{net}} \) done at each joint is not nil (Table 1). Muscles of the ankle are doing more positive than negative work, whereas at the level of the knee and the hip, muscles are doing more negative than positive work. During step 0, \( W_{\text{net}} \) is positive. The work done at the level of the ankle and the knee are not modified, as compared to control steps. The additional work is provided by the hip extensor muscles (Figs. 4 and 7), which are doing positive work during contact (during control steps, these muscles are doing negative work).

However, the balance of the work presented in Table 1 does not take into account the work that can be transferred between joints through poly-articular muscles. Indeed, poly-articular muscles can do positive work at one joint and at the same time negative work at another joint. Furthermore the balance of work done on the COM and at each joint (Fig. 4) does not take into account the internal work done to move the limb segments relative to the COM.

Belli et al. (2002) showed that when running speed increases, peak joint power increases at all joints and that the highest changes were observed in the hip joint. Furthermore with increasing speed, no significant changes in the peak of the muscular moments were observed at the level of the ankle, but significant increases were observed at the level of the knee and the hip. Our results confirm these observations. When a runner jumps over a barrier, the biggest changes are observed at the level of the hip: the peak moment at the hip (Fig. 7) and \( W_{\text{net},h} \) (Table 1) are strongly increased. On the contrary at the level of the ankle, the peak moment, the peak power (Fig. 5) and \( W_{\text{net},a} \) (Table 1) hardly change. Belli et al. (2002) suggested that during running, the role of the ankle and knee extensors is to generate joint stiffness during contact, while hip extensors are the prime forward movers of the body. By contrast, when jumping over an obstacle, the power generated at the level of the hip seems too low to define the hip muscles as “prime movers”. Even if the muscular power generated at the hip is low, hip extensor muscles could contribute to the extension of the knee and plantar flexion of the ankle, through the action of bi-articular muscles. Indeed, Van Ingen Schenau et al. (1987) have demonstrated that in jumping, the gluteus maximus muscle could develop power that is used for knee extension and to plant flexion work by the tendinous actions of both the rectus femoris and the gastrocnemius muscles. The same phenomenon could occur during step-1 to accelerate the COM forwards and during step 0 to lift and accelerate the COM upwards.

4.4. Changes in leg-stiffness, joint stiffness and lower limb orientation during step-1 and step 0

During step-1, the overall stiffness \( k_{\text{leg}} \) is reduced (Table 1). As explained by Mauroy et al. (2012), this leads to a lowering and an acceleration of the COM. The lowering of the COM is due to the fact that during the second part of contact, the knee and the ankle are not extending as much as during steady-state running. The reasons for this preparatory step are discussed by Mauroy et al. (2012).

The lower \( k_{\text{leg}} \) is due to a lower stiffness at the level of the knee and ankle (Table 1). In turn, the lower \( k_a \) and \( k_h \) are due to a smaller net muscular moment at these joints. At the level of the knee, the smaller \( k_h \) is also due to change in the geometry of the leg-segments, especially at the end of contact (see average values in Fig. 8). This suggests that the lower \( M_z \) is due to a lower

![Fig. 8](image-url) Lever arm of the ground reaction force at the lower limb joints during contact of steps preceding the jump over a 0.65 m-high barrier while approaching at ~ 15 km h⁻¹. The lever arms \( b_h \), \( b_k \) and \( b_a \) are the distance between the ground reaction force vector (F) and the center of rotation of the hip, knee and ankle, respectively. When \( b \) is positive, the force \( F \) generates a moment in (dorsiflexion, which generates a muscular moment in extension (or plantar flexion). When \( b \) is negative, \( F \) generates a moment in extension (or plantar flexion), which generates a muscular moment in (dorsi-)flexion. Others indications are as in Fig. 2.
activation of the muscle, which, in turn, leads to a smaller $k_a$ and to a smaller amplitude of $F$. At the level of the knee, the lever arm is modified during the second part of contact: contrary to steady-state running, the knee extensor muscles are pushing at the end of contact to increase the forward velocity of the COM. At the level of the hip, the role of the increased eccentric contraction (Fig. 7) is to keep the COM in a low position while the ankle and knee muscles are pushing the COM forwards. In addition, during the last 20% of contact, the vector $F$ becomes more vertical than the leg-spring (Fig. 2). Consequently, $F$ generates a moment that tends to rotate the trunk downwards and helps to keep the COM in a low position. Van Caekenbergh et al. (2013) have also observed a change in the general direction of $F$ when the COM accelerates during running overground.

During step 0, the overall stiffness $k_{leg}$ is increased (Table 1), which increases an increase of the vertical velocity and a lift of the COM with a decrease of its forward velocity. The increase in $k_{leg}$ is due to both an increase in $k_a$ and $k_k$: this is most likely due to a greater muscular activation, which stiffens the ankle and the knee and generates a greater amplitude of $F$ (Devita and Skelly, 1992). In the knee, there are significant moments in flexion at the beginning and at the end of contact. As suggested by Gunther and Blickhan (2002), this initial flexor moment pre-determines the flexion of the shank since an extension of the knee at touchdown would be disastrous. During step 0, this flexor moment is increased because the leg is touching the ground more horizontally than in control steps. The role of the flexor moment at the end of contact is to brake the extension movement of the knee before takeoff. By contrast to step-1, the vector $F$ becomes more horizontal than the leg-spring during the last 20% of contact (Fig. 2). So, $F$ generates a moment that tends to rotate the trunk backwards and upwards, and participates to the lift of the COM.

When running speed increases, ankle joint stiffness ($k_a$) changes little and the knee joint stiffness ($k_k$) is the major modulator of $k_{leg}$ (Arampatzis et al., 1999; Brughelli and Cronin, 2008; Gunther and Blickhan, 2002). Several studies have also examined the relative influence of $k_a$ and $k_k$ on $k_{leg}$ during hopping but results are, at best, ambiguous. According to Farley et al. (1998), humans adjust leg stiffness to accommodate for differences in surface stiffness primarily by modulating ankle stiffness and secondarily by modulating knee angle at touchdown. In their study, Hobara et al. (2009) evaluated leg and joint stiffness of the hip, knee and ankle: they found that knee stiffness was significantly higher than ankle and hip stiffness. Further, their regression model showed that only $k_a$ was significantly correlated with $k_{leg}$. The study of Kuitunen et al. (2011) suggests that when hopping with short contact period, $k_{leg}$ is modulated by $k_a$ and that $k_k$ is correlated with the jumping height. According to Butler et al. (2003), modulation of the joint stiffness may be related, at least in part, to the foot strike pattern: during hopping and running, if the forefoot strikes first the ground, the knee is stiffer than the ankle, conversely during rear foot landing, the ankle is stiffer than the knee. This hypothesis is corroborated by the observation of Laughton et al. (2003): as compared to rear foot runners, $k_a$ was greater and $k_k$ was lower in forefoot runners. These authors attributed the changes in joint stiffness to the decrease in knee excursion and increase in ankle excursion in the forefoot strike, as compared to the rear foot strike.

Vanrenterghem et al. (2004) have measured the net muscular moment at the level of the lower limb joints, during a vertical jump of different height (25%, 50%, 75% and 100% of the maximal height, $H$). These authors showed that the net muscular moment at the ankle does not increase anymore for jumps higher than 50% of $H$, while the muscular moment at the hip and the knee continues to increase with the height of the jump. In a following study, it should be interesting to vary the obstacle height and the approaching speed to understand how the net muscular moment and joint stiffness are modulated with these two factors.

**Conflict of interest statement**

There is no conflict of interest, i.e., there are no financial and personal relationships with other people or organization that could inappropriately influence this work.

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**Appendix A. Supplementary material**

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jbiomech.2013.10.039.

**References**


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