Kinematic, kinetic and EMG patterns during downward squatting

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Abstract

The aim of this study was to investigate the kinematic, kinetic, and electromyographic pattern before, during and after downward squatting when the trunk movement is restricted in the sagittal plane. Eight healthy subjects performed downward squatting at two different positions, semisquatting (40° knee flexion) and half squatting (70° knee flexion). Electromyographic responses of the vastus medialis oblique, vastus medialis longus, rectus femoris, vastus lateralis, biceps femoris, semitendineous, gastrocnemius lateralis, and tibialis anterior were recorded. The kinematics of the major joints were reconstructed using an optoelectronic system. The center of pressure (COP) was obtained using data collected from one force plate, and the ankle and knee joint torques were calculated using inverse dynamics. In the upright position there were small changes in the COP and in the knee and ankle joint torques. The tibialis anterior provoked the disruption of this upright position initiating the squat. During the acceleration phase of the squat the COP moved posteriorly, the knee joint torque remained in flexion and there was no measurable muscle activation. As the body went into the deceleration phase, the knee joint torque increased towards extension with major muscle activities being observed in the four heads of the quadriceps. Understanding these kinematic, kinetic and EMG strategies before, during and after the squat is expected to be beneficial to practitioners for utilizing squatting as a task for improving motor function.
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1. Introduction

The dynamic squatting exercise is an important component of several training programs in physical therapy and in a variety of sports. More specifically, the squat has been used as part of treatment of ligament lesions (Cerulli et al., 2002; Fleming et al., 2003; Heijne et al., 2004), patellofemoral dysfunctions (Steikamp et al., 1993; Witvrouw et al., 2000), total joint replacement (Kuster, 2002), and ankle instability (Hertel, 2000; Sammarco and Sammarco,

2003). Squatting down is performed in a continuous motion at the 40° (semisquatting), 70–100° (half squatting) and larger than 100° (deep squatting) (Escamilla et al., 2001).

Several studies have described the patterns of the kinematics, kinetics, and muscle activities of the knee and other joints during the squat (Bobbert et al., 1996; Cheron et al., 1997; Dan et al., 1999; Escamilla et al., 1998, 2001; Flanagan et al., 2003; Hase et al., 2004; Isear et al., 1997; McCaw and Melrose, 1999; Ninos et al., 1997; Ridderihoff et al., 1999; Stensdotter et al., 2003; Wretenberg et al., 1996; Zeller et al., 2003). The comparison across these studies is compromised for several reasons. In some studies the task was the jump squat (Bobbert et al., 1996; Ridderihoff et al., 1999) or the description of squatting was restricted to one (Escamilla et al., 1998) or two joints (Flanagan et al.,

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2003; Isear et al., 1997; Wretenberg et al., 1996). In other studies were not analyzed together kinematics, kinetics, and electromyography patterns (Cheron et al., 1997; Dan et al., 1999; Escamilla et al., 2001; Hase et al., 2004; McCaw and Melrose, 1999; Ninos et al., 1997; Stensdotter et al., 2003; Zeller et al., 2003), except the study by Flanagan et al. (2003). However, in this study the correlation between the kinetics, the kinematics and the EMG patterns were not examined.

The squat is triggered by a muscle response and the mechanism used by the central nervous system to control this response is still unclear. Initially it requires unlocking of the upright position and to generate hip flexion, knee flexion, and ankle dorsiflexion. It has been advocated that the unlocking of the upright position for squatting is initiated by suppression of the medial hamstrings and the activation of tibialis anterior, despite the initial direction of the trunk movements (Cheron et al., 1997). More recently, Hase et al. (2004) showed that the initial mechanism to execute the squat is characterized by deactivation of the erector spinae (ES) collapsing the trunk. However, the initial direction of the COP on the ground varied with the ankle muscles involved in unlocking the upright posture.

One explanation for the variety of strategies to initiate squat reported by Hase et al. (2004) could be related to differences in the positions of the upper and lower limbs. Therefore, our first hypothesis is that if the squat is performed with similar movement kinematics in both the upper and lower limbs, one would be able to identify the squatting strategy, in terms of kinematic, kinetic, and muscle activity responses.

Also, there is a possibility that the initial phase of the squat is related to the mechanical demands in the way the squat is performed. We believe that a good descriptive study correlating the electromyography, kinematic, and kinetic data of the squat in a meaningful way is a necessary condition to understand the mechanical demands of this task, but this analysis is still missing in the literature. The major goal of this study is to fulfill this gap.

Several authors (Cheron et al., 1997; Gurfinkel et al., 1974; Hase et al., 2004) have reported small activities of the plantar flexor muscles in the upright position. The correction of upright balance is probably done by the intrinsic stiffness of the muscles (Gurfinkel et al., 1974). Based on this study we predict that during the upright position and before squatting down, the EMG activities of the muscles crossing the ankle and knee joints would also be very small, and the small changes in the ankle and knee joint torque would probably be related to the intrinsic stiffness of these muscles.

Before squatting is initiated, a pre-programmed response of the tibialis anterior would increase ankle joint dorsiflexion torque disrupting the postural equilibrium as shown by Cheron et al. (1997). Once the body starts to accelerate towards the downward squat, we hypothesize that the EMG activities of the major muscles crossing the knee joint would be silent and its joint torque would remain unchanged, since the gravitational force would cause the flexion of the knee. This hypothesis is based on the observation that the quadriceps and hamstring muscles (Cheron et al., 1997; Dan et al., 1999) are silent during the acceleration phase of the squat.

During the deceleration phase of the squat we predict that the major EMG response would occur in the quadriceps muscle, accompanied by a strong increase of the knee extension torque to oppose the free fall of the body. This hypothesis was based on the increased EMG activities of the quadriceps during the deceleration phase of the movement (Cheron et al., 1997; Dan et al., 1999; Hase et al., 2004; Isear et al., 1997).

The alignment of the patella depends on the equilibrium of the forces generated by each head of the quadriceps (Lieb and Perry, 1968; Voight and Wieder, 1991; Witvrouw et al., 1996), and still there are several controversies about the contribution of each portion of the quadriceps (Karst and Willet, 1995; Voight and Wieder, 1991; Witvrouw et al., 1996). The final goal of this study was to describe the contribution of each head of the quadriceps during the acceleration and deceleration phases of the squat, since other studies (Escamilla et al., 1998; Isear et al., 1997; Wretenberg et al., 1996) have shown that the EMG activity of the vasti were larger than the rectus femoris.

Here we show that the kinetic and EMG pattern before, during and after the downward squat can be identified if the task is reproducible across trials and subjects. We did that by having the subject's squat with similar angular excursions of the major joints involved and similar linear translation of the body. We believe that a description of the squatting strategy would guide the selection and inclusion of this task in different training and rehabilitation programs.

2. Materials and methods

2.1. Subjects

Eight healthy undergraduate students, four women (mean age 21.8 years; SD = 0.61) and four men (mean age 22.3 years; SD = 1.62), participated in this study. All subjects were right-handed. The medical histories of all the subjects were reviewed, and subjects without any history of neurological or orthopedic dysfunction, surgery or pain in the spine and lower extremities, were selected. Before the collection of data, the subjects signed an informed consent for participation in this study, approved by the University of Ribeirão Preto's Committee for Ethics in Research. The average weight and height of the subjects were, respectively, 65.12 kg (SD = 18.9) and 1.68 m (SD = 0.09).

2.2. Instrumentation

Bipolar surface electrodes (model DE2.2L, DelSYS Inc., Boston, MA, USA) were placed on the following muscles only on the right lower limb: vastus medialis oblique (VMO), vastus medialis longus (VML), rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF), semitendineous (ST), gastrocnemius lateralis (GL) and tibialis anterior (TA), after the skin surface was shaved,

abraded, and cleaned with alcohol. The EMG signals were amplified (×2000), band-pass filtered (20–450 Hz) and recorded. The data were digitized at 12 bits and collected by an IBM computer at 1000 Hz.

The LEDs (light emitting diode) were fixed over the center of the right shoulder, hip, knee and ankle joints (lateral aspect of the acromion; greater trochanter; lateral epicondyle of the femur; and the lateral malleolus) and over the calcaneus, fifth metatarsal head and the posterior corner of the force plate. The LED emissions were captured at a frequency of 100 Hz using a three-dimensional optical system (OPTOTRAK® 3020, Northern Digital Inc., Waterloo, Ontario, CA).

A force plate (AMTI OR6-5, Watertown, MA, USA) was used to record the ground reaction forces (*Fx*, *Fy*, and *Fz*) and the force moments (*Mx*, *My*, and *Mz*) in orthogonal directions, at a sampling frequency of 1000 Hz (Fig. 1). The signals were amplified (×4000), band-pass filtered (10–1050 Hz) and recorded.
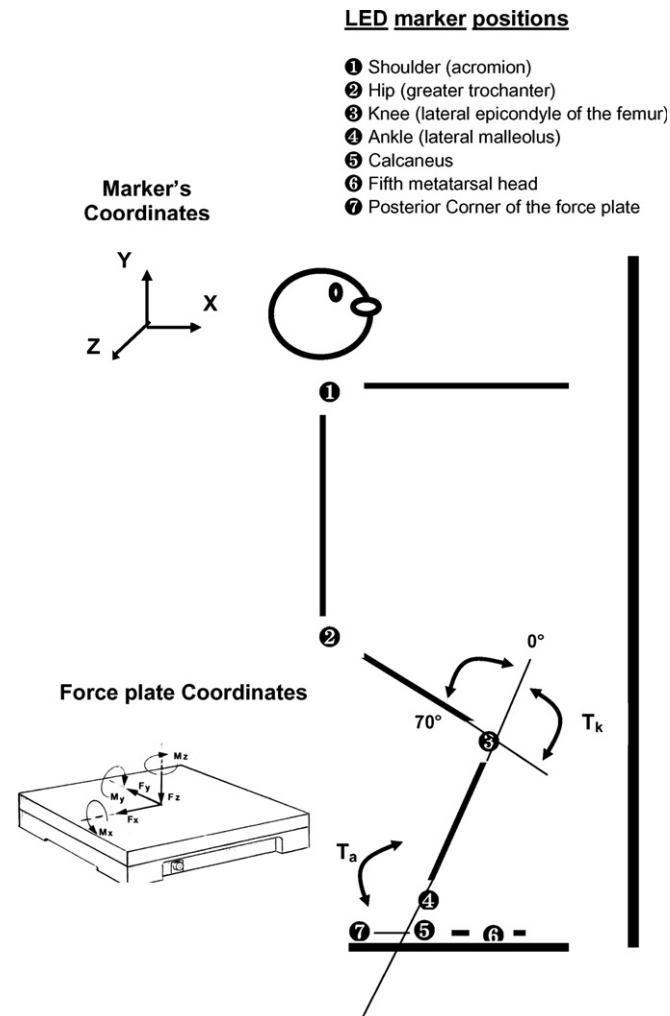

Fig. 1. This figure shows the final position of the HS task where the subjects were instructed to keep the distance between the fingers (the distal part of the rigid body) and a frontal plane (a glass panel placed 15 cm in front of the body) constant. The LED marker positions, ground reaction forces in the directions (*Fx*, *Fy*, and *Fz*), torque in the coordinate *y* (*My*) and the ankle (*T*a) and knee (*T*k) joint torques are also shown. Notice that there are different reference systems for the optical system and the force plate. This difference was later adjusted during data processing (code in MatLab).

2.3. Procedure

Subjects performed the squatting from an initial upright position, in such a way so as to induce comparable angular excursion (ankle, knee, and hip joints) and linear translation of the trunk and lower limb, both within and between subjects. These kinematic similarities were achieved by asking the subjects to keep the upper arm elevated to 90° at the shoulder joint, just in front of the body, and use it as a single rigid-body (without moving the elbow, wrist, and hand) to guide the movement. During the squat, subjects were instructed to keep the distance between the fingers of the right hand (the distal part of the rigid body) on a frontal plane, made of a glass panel (placed 15 cm in front of the body) constant (see Fig. 1). All subjects were able to follow this instruction.

Squatting was performed with the right foot on the force plate and the left on a stable wooden platform and the subjects were instructed to maintain the feet in this position during squatting, without any linear translation movement of the feet. For each subject, two marks made of cotton were placed on the glass panel, to guide the upper arm linear movement, in such a way so as to obtain 40° and 70° of knee flexion during the squat, respectively, for the semisquatting (SS) and half squatting (HS) tasks.

At the initial upright position, the subjects were required to squat as fast as possible, after hearing a verbal command to do so, and stay on the target for 1 s. The subject performed a series of 10 movements for each of the two target distances (SS and HS).

2.4. Data processing

The electromyography (EMG) signals, the force plate and three-dimensional coordinates of the LEDs markers were synchronized by ODAU II – Optotrak Data Acquisition Unit II, and later mathematically processed in a MatLab code (Math Works Inc., version 6.0). The data processing allowed the calculation of the angular excursion of the ankle, knee, and hip joints, and the linear displacements of the center of these joints. Also, these angles were differentiated to obtain angular velocity and acceleration of the joints. The anterior–posterior position of the center of pressure (COP) was defined as the moment in the *y* coordinate (*My*) divided by vertical force (*Fz*). The COP locations in the anterior–posterior direction were reported as a percentage of the longitudinal foot length (from the most posterior tip of the heel to toe tip) of each subject.

The anthropometric data (length of foot, leg, and shank segments) were obtained from the *X* and *Y* marks placed at the center of each joint. The center of mass and moment of inertia of each segment were calculated based on weight and sex of each subject using Zatsiorsky's model modified by De Leva (1996). The joint torque of the knee and ankle was normalized to each subject's weight. The torques of the ankle and knee joints were calculated using inverse dynamics based on the equations below:

$$Fx_{foot} = M_{foot} * ax_{foot} - FRSx$$
$$Fy_{foot} = M_{foot} * g - FRSy - M_{foot} * ay_{foot}$$
$$T_{ankle} = -FRSy * (CPx - XCM_{foot}) - FRSx * YCM_{foot}$$
$$+ Fx_{foot} * (Y_4 - YCM_{foot}) + Fy_{foot} * (XCM_{foot} - X_4) + I_{foot} * \alpha_{foot}$$
$$Fy_{shank} = M_{shank} * ay_{shank} + Fy_{foot} + M_{shank} * g$$
$$Fx_{shank} = M_{shank} * ax_{shank} + Fx_{foot}$$
$$T_{knee} = T_a + Fx_{shank} * (Y_3 - YCM_{shank}) - Fy_{shank} * (X_3 - XCM_{shank})$$
$$+ Fx_{foot} * (YCM_{shank} - Y_4) - Fy_{foot} * (XCM_{shank} - X_4)$$
$$+ I_{shank} * \alpha_{shank}$$

where, M represents the mass in kg, ax is the acceleration of the X coordinate of the center of mass, $FRSx$ the force in the horizontal axis of the plate force, g the acceleration due to gravity (9.8 m/s^2), $FRSy$ the force in the vertical axis of the force plate, ay the acceleration of the Y coordinate of the center of mass, T the joint torque, CPx the COP position in the antero–posterior direction, XCM the center of mass position in the X coordinate, YCM the center of mass position in the Y coordinate, Y_4 and X_4 are the coordinates of the ankle LED, I the inertial moment, α the angular acceleration, and Y_3 and X_3 are the coordinates of the shank.

The EMG signals collected during the movements were rectified, filtered (low-pass at 20 Hz using a second-order Butterworth filter) and normalized to the averaged EMG signal recorded for the tested muscle during maximum voluntary isometric contraction (MVIC). The averaged EMG of the MVIC was calculated within the 500–1000 ms interval from the beginning of the isometric contraction. For all MVIC tests the subject was sitting in a comfortable chair. The MVIC of all portions of the quadriceps was tested with the knee of the subject fixed manually at 20° of flexion (0° equal to full extension). The MVIC of the biceps femoris and semitendineous was tested with the knee of the subject fixed manually at 90°, and that of tibialis anterior and gastrocnemius, with the knee at full extension.

The averaged data were calculated for the COP displacement, ankle and knee joint torques, and EMG activities during eight movement phases which was based on the ankle and knee angular velocities: Phases 1–3, encompass three identical intervals of 100 ms each, calculated in sequence just before the knee velocity first achieves 5% of its peak. Phases 1 and 2 characterize the upright position, and phase 3, the pre-squatting period. Phases 4 and 5 define the acceleration and the deceleration time of the squat, and include, respectively, the interval from the end of phase 3 to the time point where knee velocity achieves its peak, and from the end of phase 4 to the time point where knee velocity returns to 5% of its peak. Phases 6–8 define the time when the body remains in the squat at the target position, for a time interval of 100 ms for each phase in sequence, following the end of phase 5. Phases 1–3 were used to establish a baseline before the task, and phases 6–8 after the end of the task. The knee angular velocity was used to calculate the phases of the movement for the knee joint torque, and EMG activities of the VMO, VML, RF, VL, BF, and ST. The ankle angular velocity was used to calculate the phases of the movement for the COP displacement, ankle joint torque, and EMG activities of the GL and TA.

2.5. Statistical analysis

ANOVA with repeated measures design was used to test the effect of movement phases (1–8) on the major dependent variables (the average values of the COP, ankle and knee joint torques, and the EMG signals from the recorded muscles) during SS and HS. A post-hoc comparison using Tukey honest significant difference was conducted to test the differences between specific phases. Alpha was set at 0.05.

3. Results

3.1. Temporal series

At the upright position (phases 1 and 2), the COP was in the middle of the foot (Fig. 2e), the ankle joint torque was towards plantar flexion (Fig. 2a) and the knee joint torque, towards flexion. The EMG activities of the gastrocnemius and tibialis anterior (Fig. 2c), vastus medialis oblique and vastus lateralis (Fig. 2d) and hamstrings (Fig. 2f) were very small.

During the pre-squatting phase (3), around 50 ms before the onset of the movement, the COP, knee joint torque and EMG activities of the vastus medialis oblique, vastus lateralis, hamstrings, and gastrocnemius had very small fluctuations. Note, however, that EMG activities of the tibialis anterior and the ankle torque changed during this time (Fig. 2c).

As the body started to accelerate towards the target (phase 4), the COP shifted towards the heel, while the ankle joint torque decreased toward plantar flexion. During this phase, the knee joint torque changed very little, and the EMG activities of the vastus medialis oblique and vastus lateralis remained silent, but there was a small increase in hamstring activity.

The deceleration phase (5) was characterized by maximal COP displacement to the tip of the toe with an abrupt fluctuation in direction. In this phase, there was a large increase in the ankle joint torque towards plantar flexion, also accompanied by increased EMG activities of the tibialis anterior. The knee joint torque drastically increased towards extension, accompanied by an abrupt and sustained EMG burst of activities in the quadriceps, with the activity of the vastus medialis oblique dominating over the vastus lateralis. In addition, there was increase in the EMG activities of the hamstrings.

At the target position (phases 6–8), the COP achieved its maximum value towards the toe tip. In addition, the ankle joint torque returned to a level similar to the upright position, and the knee joint torque decreased in magnitude and stayed towards extension after the end of the movement. Similar accommodation was observed in the EMG activities of the vastus medialis oblique, vastus lateralis, and hamstrings.

In general, the kinematic, kinetic, and EMG behaviors reported above for this subject during the HS were qualitatively representative of what was observed for all the seven other subjects analyzed in the two tasks (SS and HS).

3.2. Linear displacement

Fig. 3 depicts the maximum linear displacement of the shoulder, hip, knee, and ankle joints at the antero–posterior (AP), cephalo–caudal (CC), and medio–lateral (ML) directions for both tasks (SS and HS). The data revealed that, overall, the subjects followed the instructions very well, and could constrain the squat to the cephalo–caudal direction, since the major linear displacement occurred in this direction. Linear displacement of the ankle joint was minimum in the other three directions. The maximum anterior linear displacements of the knee, hip, and shoulder were, respectively, around 16, 4, and 4 cm for semisquatting, and these values were 20, 5, and 5 cm for half
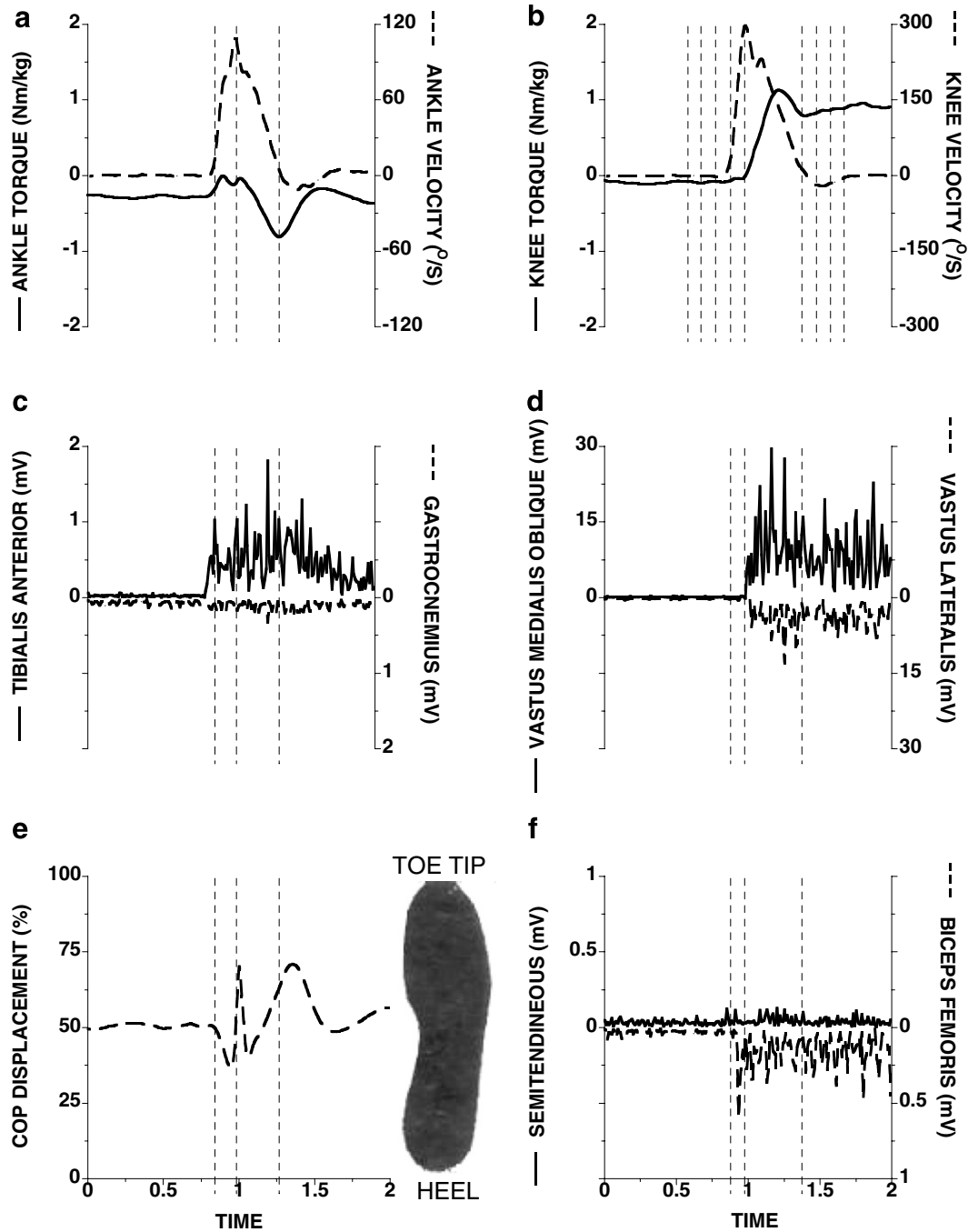
Fig. 2. This figure depicts the ankle (a) and knee (b) joint torques and velocities; the muscle activities of the tibialis anterior, gastrocnemius lateralis (c), vastus medialis oblique, vastus lateralis (d), biceps femoris and semitendineous (f) normalized to MVIC; and the displacement of the COP (e) during half squatting performed by one subject. Vertical dotted lines in a, c, d, e, and f represent the acceleration and deceleration phases. In b the lines represent the eight phases of the movement.

squatting. Note that the shoulder, hip, knee, and ankle linear displacements towards the lateral direction were less than 3 cm for either task.

3.3. Angular displacement

The average angular displacements and standard error (SE) across all subjects during the SS task were 21°

(SE = 2), 48° (SE = 2), and 20° (SE = 0.8), respectively, for hip, knee, and ankle joints. For the HS task, these values were 42° (SE = 4), 70° (SE = 3), and 28° (SE = 2), respectively. These data show that all subjects performed the tasks with similar involvement of the three major joints; that the major movement occurred at the knee; and that the movements at the three joints were larger for the HS, as compared to the SS task.
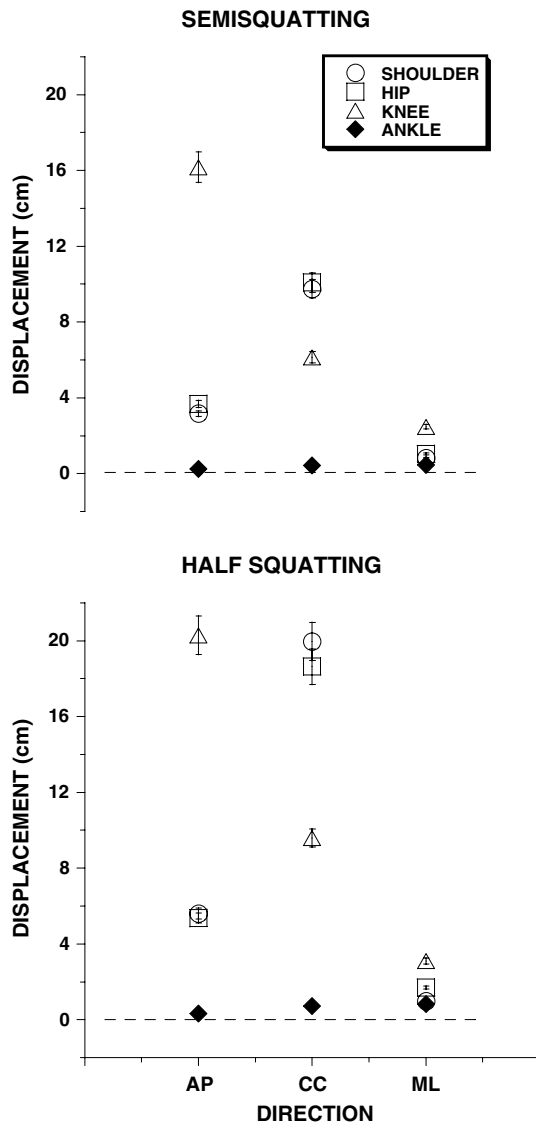
SEMISQUATTING

HALF SQUATTING

Fig. 3. This figure depicts the maximum linear displacement of the LED markers fixed on the shoulder, hip, knee, and ankle joints at the antero–posterior (AP), cephalo–caldal (CC), and medio–lateral (ML) directions for the semisquatting and half squatting tasks.

3.4. COP and joint torques

Fig. 4 (left panel) depicts the average data across all subjects for the COP (a), knee (c), and ankle (e) joint torques for each of the eight phases of the movement (see method) during the half squatting task. At the initial upright position, the COP was at the level of the cuneiforms. During the acceleration phase (AC), the COP moved towards the direction of the heel, and then returned to the toe tip direction during the ankle deceleration phase (DEC) to stay close to the tip of the toes at the end of squatting. The ANOVA revealed the main effect of the movement phases ($F_{(7,49)} = 11.38$; $p = 0.000$). The post-hoc analysis revealed that the COP displacement changed from phases 3 to 4, from phases 4 to 5, and from phases 5 to 6 ($p < 0.05$).

The knee joint torque (Fig. 4c) was a flexion torque before the movement onset (phases 1–3) and during the acceleration phase (phase 4). It reverted into extension during the deceleration phase (phase 5) and stayed in extension at the end of the movement (phases 6–8). These observations were confirmed by the ANOVA test that showed the main effect of the phase ($F_{(7,49)} = 82.70$; $p = 0.000$). The post-hoc revealed that the knee joint torques changed from phases 4 to 5 ($p = 0.000$).

The averaged ankle joint torque was always in plantar flexion before, during and after the movement (Fig. 4e). The ANOVA revealed the main effect of the movement phases ($F_{(7,49)} = 12.14$; $p = 0.000$). The post-hoc analysis showed that the ankle joint torque changed from phases 3 to 4, from phases 4 to 5, and from phases 5 to 6 ($p < 0.05$).

The magnitude of the COP displacement and joint torques of the ankle and knee varied between both the tasks, but the shape of the changes of these variables for the HS was also preserved for the SS task (data not presented here).

3.5. Electromyography

Fig. 4b, d, and f (right panel) depict the average EMG activity of all recorded muscles across all subjects calculated for the eight phases of the movement during the HS task.

The ANOVA revealed a main effect of type of the agonist (quadriceps) muscle ($F_{(3,21)} = 5.95$; $p < 0.004$), and the movement phase ($F_{(7,49)} = 15.04$; $p = 0.000$) and an interaction between the two factors ($F_{(21,147)} = 5.18$; $p = 0.000$). A post-hoc analysis revealed that the main effect of type of muscle was due to increased amount of EMG activities during phases 5–8, in the following sequence: vastus medialis oblique, vastus lateralis, vastus medialis longus, and rectus femoris ($p < 0.002$). The amount of activities of these muscles was also indistinguishable during the movement phases 1–4 and 5–8 ($p = 0.99$).

The ANOVA did not reveal any effect of movement phases for semitendineous ($F_{(1,7)} = 1.59$; $p < 0.1609$), but revealed differences for the biceps femoris ($F_{(1,7)} = 2.14$ $p < 0.05$). The post-hoc showed increased amount of muscle activities of the biceps femoris and semitendineous from phases 3–5 ($p < 0.05$) (Fig. 4d).

Fig. 4f depicts the gastrocnemius and tibialis anterior activities. The ANOVA showed that the amount of EMG activities of the gastrocnemius ($F_{(7,49)} = 2.95$; $p < 0.011$) and tibialis anterior ($F_{(7,49)} = 12.63$; $p = 0.000$) changed with the movement phase. A post-hoc analysis revealed that the muscle activity of the tibialis anterior changed from phases 2 to 3 (pre-squatting phase), and also from phases 3 to 4, while the gastrocnemius activity changed from phases 4 to 5 ($p > 0.05$).

The quantity of the EMG activity of the muscles reported above changed with the task, but the shape of
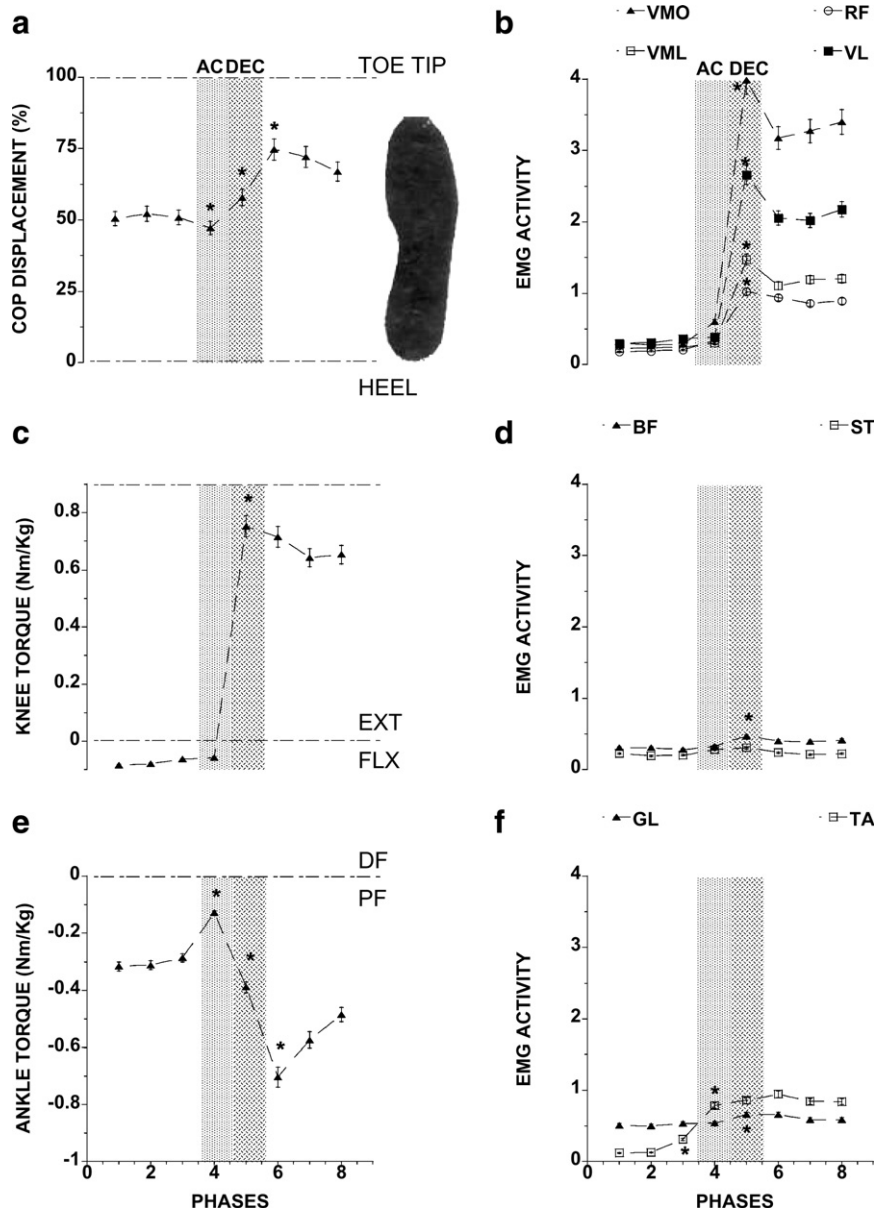
Fig. 4. This figure depicts the average across all subjects of the COP (a), knee (c) and ankle (e) joint torques (left panel) and the EMG activities (right panel) of all muscles calculated for the eight phases of the movement during the half-squatting task. The EMG activity in b is of the vastus medialis oblique (VMO), vastus medialis longus (VML), rectus femoris (RF) and vastus lateralis (VL), in (d), of the biceps femoris (BF) and semitendineous (ST), and in f, gastrocnemius lateralis (GL) and tibialis anterior (TA). The two vertical shaded bars represent, respectively, the acceleration (AC – dotted bar) and deceleration (DEC – hatched bar) phases.

the changes in the muscle activity was similar between the HS and the SS task (data not shown here).

4. Discussion

The experiment was successful in constraining the squat to the sagittal plane, and in keeping the amount of ankle, knee, and hip angular excursion similar across all subjects. The linear displacement of the body segments was also comparable across subjects (Fig. 3). Under this constrained condition, we saw the emergence of a clear kinetic and EMG pattern during the squat, as predicted by our initial hypothesis.

4.1. Kinetic and EMG strategy before downward squat

During the initial upright position (phases 1 and 2, Fig. 4a), just before the downward squat, the COP was projected anteriorly, around 50% of the length of the foot size measured from the heel. At this position, the ankle joint torque was towards plantar flexion (Fig. 4c) due to the small muscle activities of the gastrocnemius lateralis, which avoided initial disruption of the postural equilibrium. This small activation of the plantar flexor muscles in the upright position was also observed in other studies (Cheron et al., 1997; Dan et al., 1999; Gurfinkel et al., 1974; Hase et al., 2004). Indeed, at this initial position,

the small displacement the COP was also reflected in a small change of the ankle torque.

During pre-squatting phase, the small and similar amount of EMG activities of the posterior (biceps femoris and semitendineous) and anterior (vastus medialis oblique, vastus medialis longus, rectus femoris, and vastus lateralis) muscles characterized a pattern of co-activation, enough to keep the knee joint torque stable and into slight flexion. Probably the intrinsic stiffness of the muscles was responsible for the correction of small changes observed in the ankle and knee joint torque, as predicted by our hypothesis based on a previous study by Gurfinkel et al. (1974).

4.2. Pre-squatting strategy

As a preparatory response of the central nervous system (CNS) to disrupt the equilibrium and initiate the squat, some authors reported decreased muscle activities of the hamstring (Cheron et al., 1997; Dan et al., 1999; Hase et al., 2004) and erector spinae (Fredericson and Powers, 2002), and increased muscle activities of the tibialis anterior (Cheron et al., 1997; Dan et al., 1999; Hase et al., 2004) around 100–150 ms, before the onset the task.

In our experiment, the hamstring and quadriceps muscle activities did not change during this preparatory phase of the squat, but the tibialis anterior activity increased (compare phases 2 and 3 of Fig. 4b). We did not record activity of the erector spinae muscle, but since the trunk was kept erect during this task (Fig. 3), probably this muscle was not inhibited before movement. The intrinsic stiffness of the knee muscles (Gurfinkel et al., 1974), during the preparatory phase of squat, could be enough to stabilize the pelvis against the gravitational force. Thus, our data favors the idea that the down squat is initiated with a pre-programmed response of the tibialis anterior (Cheron et al., 1997) that was accompanied by a decrease in the plantar flexor torque. Taken together, these studies may show that the activation or inhibition of the other postural distal muscles to the ankle joint (Cheron et al., 1997; Dan et al., 1999; Hase et al., 2004) may depend on the initial position of the COP, determined by the position of the upper segments and the trunk and head.

4.3. Squatting strategy during the acceleration phase

With disruption of the upright equilibrium by the anticipatory response of the tibialis anterior, the body starts to fall freely due to the gravitational force. At this phase, the COP is displaced posteriorly towards the heel and the knee joint torque remains unchanged towards flexion. This explains why during the acceleration phase of the squat the muscle activities of the four heads of the quadriceps (vastus medialis oblique, vastus medialis longus, rectus femoris and vastus lateralis) were very small (Fig. 4b). These observations confirm the results reported by other authors (see Figs. 7 and 8 in Cheron et al. (1997)) and (see Fig. 2 in Dan et al. (1999)) showing small muscle activ-

ity of the quadriceps during the acceleration phase of squatting. Since the gravitational force is accelerating the knee joint into flexion there is also no need, as observed, for increased muscle activity of the biceps femoris and semitendineous (Fig. 4d). Similar EMG results were reported in other studies (Cheron et al., 1997; Dan et al., 1999; Hase et al., 2004; Isear et al., 1997).

Some authors (Dan et al., 1999) reported that during the acceleration phase of the down squatting, the plantar flexors are inhibited and the tibialis anterior is activated. In our study, the gastrocnemius and tibialis anterior were co-activated during the acceleration phase (Fig. 4), with the activity of the tibialis anterior being predominant. An important question that arises is why the plantar flexion joint torque at the ankle decreased when the COP was displaced towards the direction of the heel. In our study, during the acceleration phase of the down squat, the trunk was kept erect, moving the COP posteriorly as the knee flexed. To avoid the body falling backwards, the amount of ankle joint torque towards plantar flexion decreased due to increased activity of the tibialis anterior. Also the degree of co-activation between the gastrocnemius and tibialis anterior probably helped to provide stability to the ankle joint that was subjected to a strong reaction force (not calculated in this experiment) during this task.

4.4. Squatting strategy during the deceleration phase

During this phase of squatting, the COP returned to the direction of the toe tip (Fig. 4a), with a strong change of the knee joint torque into extension (Fig. 4c) and the ankle joint torque moving towards the plantar flexion direction (Fig. 4e). The knee extensor joint torque was generated by the strong activation of the quadriceps (vastus medialis oblique, vastus medialis longus, vastus lateralis, and rectus femoris), which acted eccentrically. The increased activation of the quadriceps during squat was also observed in several studies (Cheron et al., 1997; Dan et al., 1999; Escamilla et al., 1998; Flanagan et al., 2003; Hase et al., 2004). The higher activities of the vastus medialis and lateralis in comparison to rectus femoris (Fig. 4b) during squatting were also reported in other studies (Escamilla et al., 1998; Isear et al., 1997; Wretenberg et al., 1996). Among the heads of the quadriceps, the amount of vastus medialis oblique activities were around 30% larger than vastus lateralis, which in turn were around 40% larger than vastus medialis longus and rectus femoris. On other hand, the small increase of the EMG activities of the biceps femoris and semitendineous probably stabilized the pelvis, avoiding excessive hip flexion (Ohkoshi et al., 1991) and helped in the stability of the knee.

The additional flexion of both ankle and knee joints displaced the thigh and shank anteriorly, favoring the displacement of COP towards the direction of the toe tip during the deceleration phase of the squat. The increased ankle plantar flexion torque prevented the body from falling anteriorly. Under this condition, one would expect to

observe a decrease in the tibialis anterior activity. Note in Fig. 3 that the ankle was displaced towards the lateral direction, probably due to the inversion of this joint. This inversion could be generated by activation of the tibialis anterior to maintain the stability of the ankle. The co-activation of the anterior and posterior muscles crossing the ankle joint was also reported in others studies (Cheron et al., 1997; Dan et al., 1999; Hase et al., 2004). Thus, our data showed that the kinematic and EMG strategy used by CNS to accelerate and decelerate the limb into squat is more complex than we previously hypothesized.

4.5. Squatting strategy at the target position

The oscillation of the body at the final position (phases 6–8) generated initially, an additional increase in the ankle plantar flexion torque that returned to the previous level. At the target, low level of quadriceps activity and the knee joint torque were demonstrated. Similar accommodation was also observed for the COP. The unchanged level of muscle activities of the tibialis anterior and gastrocnemius muscles, after the end of the movement, show that the observed decreasing of the ankle joint torque occurred without the need of additional muscle activities.

4.6. Clinical implications

The squatting exercise has been included in several protocols to treat musculoskeletal disorders, such as patellofemoral pain syndrome and other hip, knee, and ankle dysfunctions (Cerulli et al., 2002; Fleming et al., 2003; Heijne et al., 2004; Hertel, 2000; Kuster, 2002; Sammarco and Sammarco, 2003; Steikamp et al., 1993; Witvrouw et al., 2000). The kinetic and EMG strategy before, during and after the squat, described here, will certainly help rehabilitation practitioners to better adjust the use of this task in improving motor function. For example, the equilibrium in the activation of the vastus medialis oblique and vastus lateralis muscles, determines the alignment of the patella in the trochlear groove (Lieb and Perry, 1968; Voight and Wieder, 1991; Witvrouw et al., 1996). The predominance of the vastus lateralis over the vastus medialis oblique could provoke the patellofemoral pain syndrome (Karst and Willet, 1995; Voight and Wieder, 1991; Witvrouw et al., 1996). Under this condition, the recovery of the function of the vastus medialis oblique should be considered to be the most important goal of rehabilitation (Crossley et al., 2001; Fredericson and Powers, 2002; Powers, 1998). Our data showed that the downward squat requires a strong vastus medialis oblique, since its activation was larger than the other heads of the quadriceps.

Acknowledgements

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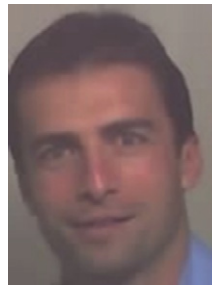
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