

## Lower Extremity Muscle Functions During Full Squats

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The purpose of this research was to determine the functions of the gluteus maximus, biceps femoris, semitendinosus, rectus femoris, vastus lateralis, soleus, gastrocnemius, and tibialis anterior muscles about their associated joints during full (deep-knee) squats. Muscle function was determined from joint kinematics, inverse dynamics, electromyography, and muscle length changes. The subjects were six experienced, male weight lifters. Analyses revealed that the prime movers during ascent were the monoarticular gluteus maximus and vasti muscles (as exemplified by vastus lateralis) and to a lesser extent the soleus muscles. The biarticular muscles functioned mainly as stabilizers of the ankle, knee, and hip joints by working eccentrically to control descent or transferring energy among the segments during ascent. During the ascent phase, the hip extensor moments of force produced the largest powers followed by the ankle plantar flexors and then the knee extensors. The hip and knee extensors provided the initial bursts of power during ascent with the ankle extensors and especially a second burst from the hip extensors adding power during the latter half of the ascent.

**Keywords:** electromyography, inverse dynamics, kinesiology

Traditionally, kinesiologists and physical educators classify muscles in several ways: by anatomical function, by type of contraction, by level of recruitment, and by work done by the muscle during a particular motion. Anatomically, muscles are defined by whether they are flexors, extensors, abductors, adductors, and so on based on their lines of action across the joints that they cross. Muscle contractions are categorized by how a muscle's length changes—concentric if the muscle shortens,

eccentric if it lengthens, and isometric when it is active but there is no change in muscle length. The recruitment level of a muscle is usually identified by the relative magnitude of its electromyogram (EMG) compared with its maximal magnitude. More difficult to define is the work done by a specific muscle and where the energy it produces is used within the musculoskeletal system. To overcome this currently unsolvable problem, the work done by the moments of force across each joint are used to estimate the net work done by all the structures that cross the joint. Since the main contributors to the work done across a joint are muscles, especially when the joint does not reach its anatomical limits, biomechanists have a partial way of determining the roles of muscles during motion.

One can, for example, analyze a simple flexor movement and observe an increasing moment of force and a simultaneous increase in the EMG of the flexor muscle. To terminate the period of flexion, an antagonistic extensor muscle may turn on to cause an extensor moment of force. The flexor muscle would be observed to be shortening during its period of contraction while the extensor muscle would be shown to be lengthening or eccentrically contracting. The situation becomes more complex when multiple joints are involved and some of the muscles cross more than one joint. For example, researchers have come to opposite conclusions when analyzing the role of biarticular muscles during the vertical jump. Bobbert and Van Ingen Schenau (1988) stated that energy was transferred distally by biarticular muscles, whereas Pandy and Zajac (1991) showed a distal-to-proximal transfer of energy. To reach their conclusion, Pandy and Zajac determined the contributions of muscles based on a musculoskeletal model of the lower extremity. They pointed out that muscles crossing a particular joint can deliver power to segments remote from the joint(s) that they cross. If only it were possible to attach power meters to the muscles to watch the flows of mechanical energy as we do to measure the flow of electrical energy to a house.

Elftman (1939a, 1939b) suggested a partial solution to this problem and applied it to walking. His approach was to calculate the powers due to the net forces and moments at each joint as well as the instantaneous

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powers of each segment. The segmental powers could then be accounted for by the flows of energy to or from the segment at each end. Winter and Robertson (1978) used his methods to show that energy could be tracked during gait and proved that during the push-off phase of walking, work generated by the ankle plantar flexor moment was used to supply energy to the foot, leg, thigh, and even the trunk by the transfer of energy through passive joint structures. However, no effort was made to identify which muscles were responsible for the various bursts of positive and negative work during the complete gait cycle.

In this study, we will apply inverse dynamics and moment power analysis to determine the work done at the joints coupled with information about various major muscles of the lower extremity to determine how the motions of the full squat are achieved. In particular, the roles of the biarticular muscles will be elucidated based on their levels of contraction (EMGs) and their states of contraction (lengthening or shortening). For example, a curious paradox can occur when two opposing biarticular muscles contract simultaneously to produce motion at both joints instead of stiffening the joints they cross. Such a situation, first described by Duchenne (in 1885, see Kuo, 2001) and Lombard (1903) and subsequently named *Lombard's paradox*, is observed when rectus femoris and biceps femoris contract concurrently during the motion of rising from a chair. The extension seen at both the hip and knee is the result of the differential moment arms of the two muscles at each joint. Since the rectus femoris has a greater moment arm across the knee, due to the patella, it creates an extensor moment at the knee. Biceps femoris has the longer moment arm at the hip so it creates an extensor moment there. Thus, simultaneous contractions of these muscles from the seated position causes extension of the both the knee and hip.

Experimentally determining how two-joint muscles contribute during a full squat requires information about muscle lengths, joint kinematics, and net moments of force. Molbech (1965) suggested that biarticular muscles of the lower extremity act in a "paradoxical" fashion when the movement is constrained or controlled. For his example, the movement consisted of having the feet motionless on the ground and the hips following a vertical track. He showed that a paradoxical situation occurred because when a biarticular muscle, such as the gastrocnemius contracted, it caused knee extension when normally it was a knee flexor. In a subsequent paper (Carlsöö & Molbech, 1966), he and Carlsöö proposed that a similar situation existed for seated cycling where knee flexors, such as the hamstrings, acted as knee extensors. They considered cycling a controlled motion since the pelvis was fixed to the seat and the feet must travel a circular path. Other studies have documented that paradoxical activity may occur during movements when several joints have reduced degrees of freedom, for example, during seated bicycling (Gregor et al., 1985; Andrews, 1987), rowing (Robertson et al.,

1988), vertical lifting (Molbech, 1965; Wilson & Robertson, 1988), sprinting (Simonsen et al., 1985), and jumping (Bobbert & Van Ingen Schenau, 1988; Pandey & Zajac, 1991; Zajac, 1993; Prilutsky & Zatsiorsky, 1994; Jacobs et al., 1996).

The purpose of this study was to determine the functions of the major lower limb muscles, particularly the biarticular muscles, during full squats (descent and ascent) based on EMG activity, inverse dynamics, moment powers and estimated muscle length changes. Past research (Molbech, 1965; Wilson & Robertson, 1988) examining biarticular muscles during full squatting has provided some evidence for the existence of paradoxical muscle activity. A study by Andrews (1985) attempted to define paradoxical activity through the examination of a first-order differential relationship between muscle length and joint angle that yields the moment arm length. Unfortunately, his method did not account for changes in muscle recruitment.

## Methods

The subjects were six male experienced weight lifters. The subjects varied in height from 1.78 to 1.90 m and in mass from 71.8 to 95.5 kg. The body was modeled as four rigid segments connected by frictionless pin joints at the hip, knee, and ankle. Segmental masses, radii of gyration, and centers of gravity were calculated from proportions described by Dempster (1955) and Plagenhoef (1971). The length of the muscles of interest (soleus, tibialis anterior, gastrocnemius, vastus lateralis, semitendinosus, biceps femoris, rectus femoris, and gluteus maximus) were calculated using Frigo and Pedotti's (1978) model with modifications by Hubley (1981) to allow scaling for different sized persons. The bar was treated as a particle with its center of gravity acting at its geometric center. Angular motion of the bar about its center of gravity was considered negligible (McLaughlin et al., 1978).

Before data collection, pairs of silver-silver chloride electrodes were placed on the muscles at locations specified by Delagi et al. (1975). Skin impedance was confirmed to be below 20 k $\Omega$  and the interelectrode distance set to 2.5 cm to reduce cross talk (Winter et al., 1994). High-input-impedance (10 M $\Omega$ ) differential amplifiers (>110 dB CMRR, 10–500 Hz band-pass) were used to obtain reliable EMG signals. The full-wave-rectified EMG signals were filtered through 2nd-order Butterworth filters with a 6-Hz cutoff frequency (Winter, 1990), yielding their linear envelopes.

Following a warm-up and rest period, the subjects were required to perform 12 full squat (knees maximally flexed) trials with 3 min of rest between trials. Six of the trials were performed unloaded as a warm-up, and the other half were performed with a load representing 80% of each subject's previously recorded maximum. The squat consisted of a 2-s descent during which the ankle, hip, and knee became flexed into a full squat followed immediately by a 2-s ascent during which the three

joints extended to return to an upright posture. The load lifted during the full squats varied from 600 to 1226 N.

The subjects executed full squats with their right feet on a force platform (Kistler 9261A). Cinematographic, electromyographic, and kinetic data were collected simultaneously. A cine camera was positioned perpendicular to the plane of motion, and all data were sampled at 50 Hz. Following the 12 trials, the subjects were required to perform three maximal isometric contractions for each muscle. To elicit the MVCs, each subject adopted a partial squat position with the heels not touching the ground and performed a maximal isometric contraction against a chain that was connected with the ground. In pretesting, this procedure was shown to produce MVCs in all of the major muscle groups that were used in this study. The EMG results were averaged and the maximum contraction values were used to detect the relative EMG activation states of the muscles during the full squats.

Within each of the two testing conditions (with and without load), linear-envelope EMG signals for each muscle were normalized over time and to maximum EMG values. These data were then averaged for each subject over six trials to yield an ensemble average EMG pattern for each muscle. All within-subject ensemble averages were then averaged to produce the across-subject grand ensemble average (Yang & Winter, 1984) for each muscle and testing condition.

The film data were digitized to an accuracy of less than 0.5 mm and then processed with the Biomech Motion Analysis System (<http://www.health.uottawa.ca/biomech/csb/biomech.htm>). The motion data were smoothed with a zero-lag, 4th-order, Butterworth filter set to a cutoff frequency of 6 Hz. Joint angular displacements and velocities were derived from the motion data and combined with the force plate data for inverse dynamics analysis that resulted in the calculation of net internal moments of force and their associated powers (Robertson & Winter, 1980) at the ankle, knee, and hip. These kinematic and kinetic data were then time normalized and averaged across subjects.

Muscle-tendon-unit lengths for each subject were calculated from relative angle changes, (Frigo & Pedotti, 1978; Hubley, 1981) normalized to their length during standing and then ensemble averaged. These averages were time normalized and then averaged across subjects, resulting in grand ensemble, muscle length histories.

## Results

A slightly greater portion of the squat was required for the descent phase (0–53%) than for the ascent phase (53–100%) based on the change from flexion to extension of the three joints. The changes that occurred in the angles of the joints are illustrated in Figure 1. During the descent, all three joints flexed, simultaneously; the reverse was seen during the ascent, in which all three

joints extended concurrently. The minimum flexion angles for all three joints occurred at the end of descent. Because there were no significant differences in the ranges of motion of the joints between the unloaded and loaded conditions, based on a dependent groups *t* test ( $p = .055$ ), and since it was the loaded conditions that were of most interest, only results from the loaded conditions are presented.

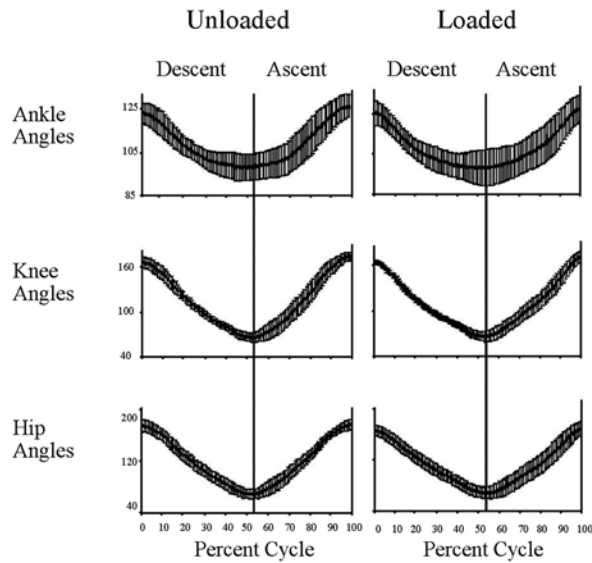
At all three joints the peak angular velocities occurred simultaneously. The peak negative angular velocity occurred at just after 10% of the cycle whereas the peak positive angular velocity occurred at 90% of the cycle. The peak angular velocities at the hip and knee joint (approximately 2 rad/s), however, were substantially higher than that of the ankle joint (<1.0 rad/s).

The hip, knee, and ankle joints had very distinct patterns of the net moments of force (Figures 2, 3, and 4). The hip and ankle joints showed extensor moments throughout ascent and descent, whereas the knee joint started and ended with a flexor moment, with an extensor moment in between. Peak moments varied between subjects but, on average, the highest peak moments were produced at the hips (maxima around –300 N·m) followed by the ankles (approx. –200 N·m) and then the knees (between  $\pm 100$  N·m).

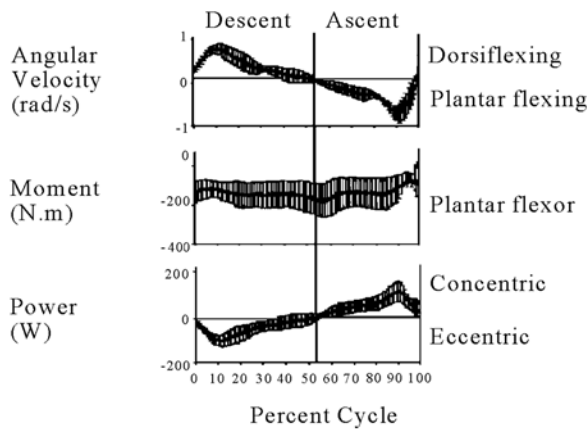
The moment powers (Figures 2, 3, and 4) at the knee differed notably from the patterns seen at the other two joints. The power patterns for both the hip and the ankle extensors were eccentric during the descent and concentric during the ascent. In contrast, power values at the knee started with the flexors acting concentrically and then with the extensors acting eccentrically for the rest of the descent. The ascent began with the extensors switching to concentric contractions and ended with the flexors working eccentrically. Again, the peak powers were highest for the hip extensors followed by the ankle plantar flexors and then the knee extensors.

The functions of the moments of force at the hip and ankle divide into two phases (Figures 2 and 4). In the descending phase, extensor moments dissipated energy in order to control the rate and amount of the descent, whereas, in the ascending portion, work was generated by extensor moments about these joints. In contrast, the functions of the knee moments of force divided into four phases (Figure 3)—two during descent and two during ascent. Initially during descent, positive work was performed by the knee flexors to unlock the knee and initiate downward motion (0–15% of the cycle). During the rest of the descent, energy was dissipated by the knee extensors in an effort to control knee flexion (15–53% of the cycle). Positive work performed by the knee extensors signaled the start of the ascent (53–85% of the cycle). Near the end of the ascent, the knee flexors started to perform negative work (acted eccentrically) to reduce the rate of knee extension and presumably prevent hyperextension (85–100% of the cycle).

The ensemble-averaged lengths of the muscles as proportions of their standing lengths during the full



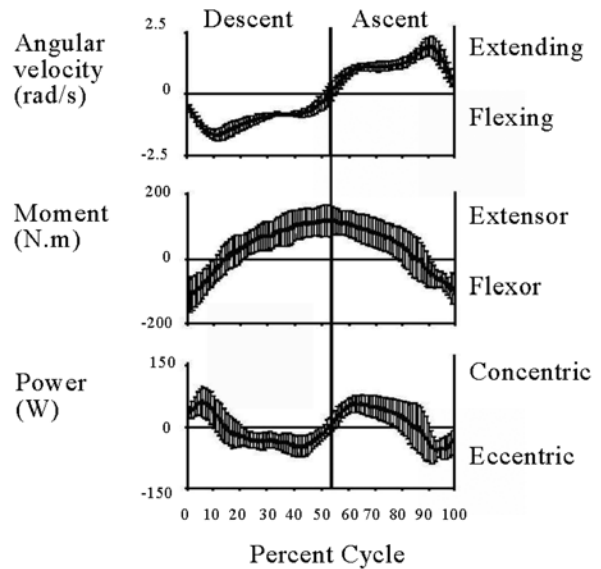
**Figure 1** — Joint angles (in degrees  $\pm 1$  SD) during loaded and unloaded full squats.



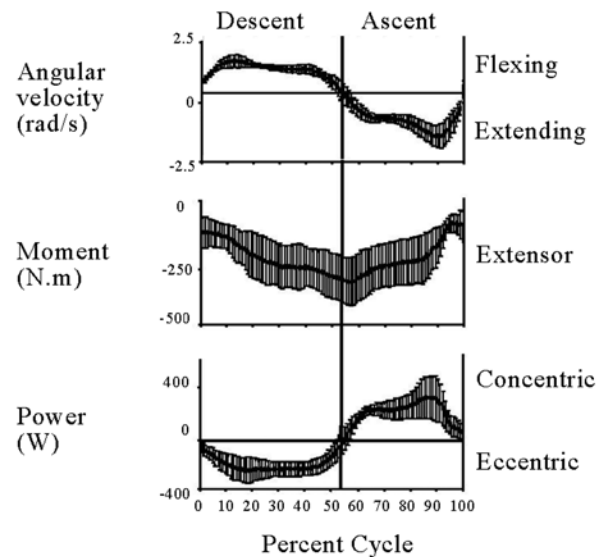
**Figure 2** — Ankle angular velocity, net moment of force, and moment power ( $\pm 1$  SD) during loaded full squats.

squats are displayed in Figure 5. Three of the monoarticular muscles acted at lengths beyond their standing lengths. Soleus, gluteus maximus (GM), and vastus lateralis (VL) all lengthened beyond their standing lengths during descent, by 7%, 29%, and 18%, respectively, before returning to their standing lengths at the end of ascent. Only the monoarticular tibialis anterior muscles shortened 5% during descent before returning to their standing lengths during ascent.

Of the biarticular muscles, the rectus femoris muscles stayed close to their standing lengths with changes of less than 2%. They were also unusual by having a bimodal pattern—lengthening then shortening during both descent and ascent. All other biarticular muscles exhibited unimodal contraction patterns—shortening on



**Figure 3** — Knee angular velocity, net moment of force, and moment power ( $\pm 1$  SD) during loaded full squats.

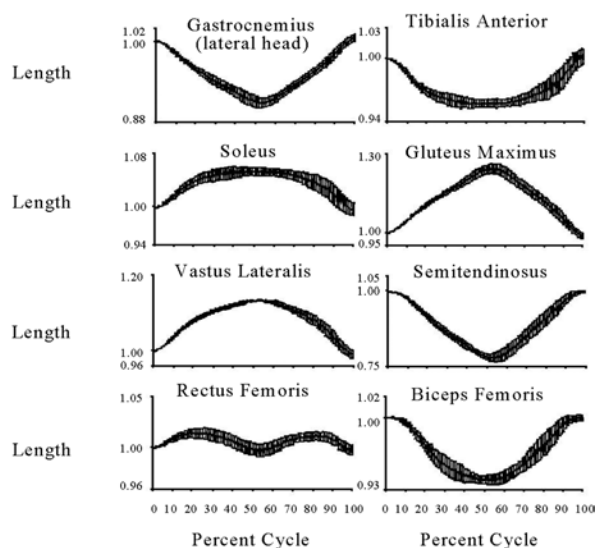


**Figure 4** — Hip angular velocity, net moment of force, and moment power ( $\pm 1$  SD) during loaded full squats.

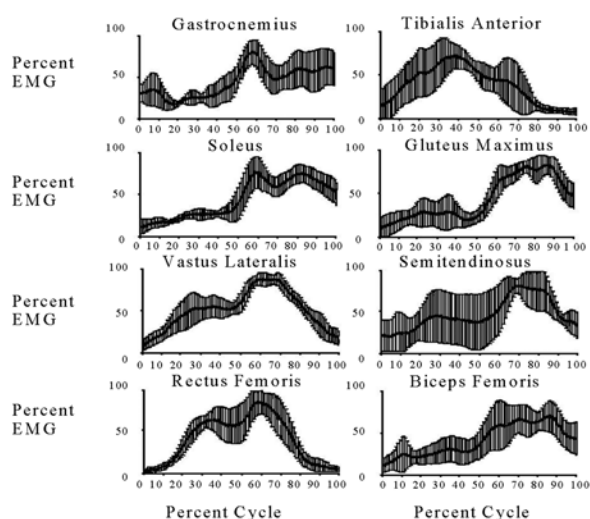
descent and lengthening on ascent. Gastrocnemius, semitendinosus, and biceps femoris each shortened by 8%, 20%, and 6%, respectively, during descent.

Linear-envelope electromyograms averaged across subjects and normalized to each subject's maximum voluntary contractions (MVCs) are displayed in Figure 6. These curves show the onset and recruitment levels of each muscle during the squatting motion. The descent phase of the full squat was characterized by tibialis anterior, vastus lateralis, and rectus femoris activity,





**Figure 5** — Lengths of the muscles ( $\pm 1$  SD) as proportions of their standing lengths during loaded full squats.



**Figure 6** — Linear-envelope EMGs ( $\pm 1$  SD) during loaded full squats as percentages of maximum voluntary contractions (MVCs).

whereas the ascent phase showed increasing levels of activity from all the muscles, excepting tibialis anterior, which decreased.

At the ankle joint, little evidence of coactivation of antagonistic muscles occurred except at the deepest part of the descent and during the early part of the ascent phase (50–70% of cycle duration). Gastrocnemius and soleus EMG patterns followed each other synergistically, and both these muscles were relatively inactive (<25% MVC) during periods of significant tibialis anterior activity. In contrast, coactivation (i.e., >25% MVC)

of the antagonistic muscles was observed at the knee and hip joints as the rectus femoris, gluteus maximus, vastus lateralis, semitendinosus, biceps femoris, and gastrocnemius contracted simultaneously during the extension (ascent) phase. EMG activity of the semitendinosus paralleled that of the biceps femoris since both are part of the hamstrings group, as did vastus lateralis and rectus femoris, both part of the quadriceps group. Thus, the hamstrings and gastrocnemius acted antagonistically to the actions of the quadriceps group at the knee while the gluteus maximus acted antagonistically to the rectus femoris at the hip during the early portion of the ascent.

## Discussion

The tibialis anterior contracted concentrically about the ankle during descent to assist dorsiflexion. Soleus, as expected, functioned eccentrically but contributed little based on its relatively low level of EMG activity. In contrast, gastrocnemius, which also had a relatively low level of recruitment, contracted concentrically. As a two-joint muscle, the role of the gastrocnemius may have been to assist knee flexion, whereas the soleus acted to limit the amount of ankle dorsiflexion during descent. This observation is supported by the fact that soleus level of recruitment increased to almost 50% MVC as the subjects reached maximum descent.

Muscle activity about the knee during descent was characterized by two periods—one of concentric work and one of eccentric work. During the initial brief period of concentric work gastrocnemius, semitendinosus, and biceps femoris acted together to initiate flexion of the knee. These muscles concentrically contracted and were active at around 25% of MVC. In particular, gastrocnemius exhibited a brief burst that combined with the two hamstring muscles was enough to unlock the knee and permit descent. Afterward, knee flexion continued with the knee extensors acting eccentrically to control and eventually terminate the descent. During the eccentric part of descent, continuous activity of the vastus lateralis contracting eccentrically was evident. Rectus femoris (RF), another knee extensor, exhibited increasing EMG activity as the descent reached maximum depth. During the second half of descent, however, RF was shortening slightly so it may have acted more as a hip flexor or as a stabilizer at both hip and knee. Since RF's length changed less than 2%, one could characterize its role as being isometric and therefore was responsible for transmitting energy across the hip and knee joints for dissipation by the knee extensors and ankle plantar flexors. This type of mechanism has been shown for jump landings by Prilutsky and Zatsiorsky (1994), but the exact nature of RF's contributions are difficult to gauge using only inverse dynamics (Zajac, 1993).

The hip moment of force was consistently extensor through the squat. During descent, the extensor moment of force did negative work to control the rate and amount

of hip flexion. Gluteus maximus contracted eccentrically throughout the descent with EMG levels starting at 10% MVC and increasing to about 25% MVC around mid-descent. The gluteals curiously reduced their activity level at maximum squat depth. Presumably, they were not needed to maintain stability or perhaps they permitted an extra degree of hip flexion that would have created a deeper counter-movement immediately before ascent. Counter-movements enable stronger contraction forces when they are done rapidly and immediately before a powerful movement (Van Ingen Schenau, 1984).

Not surprisingly, during the ascent phase all three moments of force were extensor and performed concentric work. The hip extensors dominated earliest and throughout the ascent, having the largest peak moments ( $>300$  N·m) and the largest peak powers ( $>200$  W at 60% of cycle time with a second peak  $>300$  N·m at 85% of cycle time). The knee extensors produced relatively the lowest powers of the three moments and only contributed positive work for the first two-thirds of the ascent. The ankle plantar flexors produced larger powers than the knee extensors but did not contribute their maximum power until near the end of the lift (at 85% of cycle time). This order of power production, from proximal (hip) to distal (ankle), is similar to that of counter-movement jumping (Nagano et al., 1998). Despite this ordering of the powers, examination of the EMGs show that all flexors and extensors (excepting tibialis anterior) were recruited almost simultaneously as compared with vertical jumping (Bobbert & Van Ingen Schenau, 1988), for which the order of recruitment was hip, knee, and then ankle muscles. This may be due to the static start and finish required for the full squat. One obvious difference with the squat was that all muscles relax at the end of the movement whereas in vertical jumping many muscles continue to contract until and after the end of ground contact.

The soleus was the major contributor to ankle extension since it concentrically contracted and was recruited almost maximally. Gastrocnemius was also heavily recruited but did no positive work during this period because it was contracting eccentrically and so could have been involved with transferring energy proximally due to its biarticular nature (Van Soest et al., 1983, Zajac, 1993; Prilutsky & Zatsiorsky, 1994). As expected, the antagonistic tibialis anterior reduced its activity level during ascent but was partly activated, presumably to stabilize the ankle against unexpected perturbations.

During the first two-thirds of ascent, the knee extensor moment did positive work. The vastus lateralis, and presumably the other vasti, contracted concentrically and were recruited near maximally. The RF, another member of the quadriceps group, was also recruited based on its high levels of EMG but did not contribute positive work to the body as it acted eccentrically through the first half of the ascent, during which the majority of the external work by the knee extensors was done. In fact, as mentioned previously, RF's lengths did

not vary much ( $<2\%$ ) so they may have acted to prevent excessive hip extension, which might result in the subject falling backward.

The antagonistic hamstrings, biceps femoris, and semitendinosus, were also recruited during this period especially at mid-ascent, but contracted eccentrically. Gastrocnemius, another biarticular knee flexor, was also actively recruited during ascent and like the hamstrings contracted eccentrically. These antagonists would appear to be working against knee extension but their combined actions may in fact assist extension. If we consider that their lines of action are both partly directed rearward, their vector sum would produce a force that pulls the knee joint backward and into extension. Such a mechanism has been suggested for biarticular muscles when the segments are not constrained, as in jumping (Zajac, 1993), but may also be true for lifting activities, in which the distal ends of the kinematic chain (i.e., the feet) are constrained by the ground. This paradoxical ability of the biarticular muscles was suggested by Molbech (1965) but was not investigated for a situation where two sets of biarticular muscles (gastrocnemius and hamstrings) acted simultaneously. The difficulty with Molbech's principle is that he assumed that the biarticular muscles shortened whereas for full squats the biarticular muscles lengthened. Thus, his paradoxical muscle activity cannot be said to have occurred during full squats.

At the hip, the gluteus maximus was clearly a major contributor to the work done. The gluteus maximus muscles contracted concentrically throughout the ascent and were actively recruited to near maximum levels especially during the first two-thirds of the ascent. Its antagonist, RF, was also heavily recruited but only during the earliest third of the ascent when it was eccentrically contracting. As mentioned previously, RF offered resistance to hip extension but may also have been fulfilling its role as a knee extensor by transmitting energy from the torso to the leg (tibia). Rectus femoris could have transmitted energy because of its relatively stiff behavior as shown but its minimal length change (Prilutsky & Zatsiorsky, 1994). At the end of ascent, RF shortened but its recruitment level was nearly zero and therefore did not contribute energy to the motion.

In conclusion, analysis of the EMG, inverse dynamics, moment powers, and muscle length changes during squatting revealed the complex relationships among the contributions of the various major muscles of the lower extremity. Not surprisingly, there was a close agreement between the results of the six participants, which supports the notion that they all performed the squat in a similar fashion. The results support Pandy and Zajac's (1991) notion that energy is provided in a proximal-to-distal sequence with the hip extensors providing the greatest contributions during ascent, followed by the ankle plantar flexors, and then the knee extensors. The important role of the knee flexors as the initiators of the squatting motion by unlocking the knee and permitting the start of descent was also identified.

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## References

- Andrews, J.G. (1985). A general method for determining the functional role of a muscle. *Journal of Biomechanical Engineering*, *107*, 348–353.
- Andrews, J.G. (1987). The functional roles of the hamstrings and quadriceps during cycling: Lombard's paradox revisited. *Journal of Biomechanics*, *20*, 565–575.
- Bobbert, M.F., & van Ingen Schenau, G.J. (1988). Coordination in vertical jumping. *Journal of Biomechanics*, *21*, 241–262.
- Carlsöö, S., & Molbeck, S. (1966). The functions of two-joint muscles in a closed muscular chain. *Acta Morphologica Neerlandico-Scandinavica*, *7*, 377–386.
- Delagi, E.F., Perotto, A., Iazzatti, I., & Morrison, D. (1975). *Anatomic guide for the electromyographer—The limbs*. Springfield, IL: C. Thomas.
- Dempster, W.T. (1955). *Space Requirements of the Seated Operator. Geometrical, Kinematic and Mechanical Aspects of the Body with Special Reference to the Limbs. WADC Technical Report* (pp. 55–159). Ohio: Wright Air Development Centre, Air Research and Development Command, United States Air Force, Wright-Patterson Air Force Base.
- Elftman, H. (1939a). Forces and energy changes in the leg during walking. *The American Journal of Physiology*, *125*, 339–356.
- Elftman, H. (1939b). The function of muscles in locomotion. *The American Journal of Physiology*, *125*, 357–366.
- Frigo, C., & Pedotti, A. (1978). Determination of muscle length during locomotion. In R.C. Nelson & C.A. Morehouse (Eds.), *Biomechanics VI-A* (pp. 355–360). Baltimore, MD: University Park Press.
- Gregor, R.J., Cavanagh, P.R., & Lafortune, M. (1985). Knee flexor moments during propulsion in cycling—A creative solution to Lombard's Paradox. *Journal of Biomechanics*, *18*, 307–316.
- Hubley, C.L. (1981). An analysis of assumptions underlying vertical jump studies used to examine work augmentation due to pre-stretch. Unpublished Master's Thesis. University of Waterloo, Waterloo.
- Jacobs, R., Bobbert, M.F., & van Ingen Schenau, G.J. (1996). Mechanical output from individual muscles during explosive leg extensions: The role of biarticular muscles. *Journal of Biomechanics*, *29*, 513–523.
- Kuo, A.D. (2001). *The action of two-joint muscles: The legacy of W. P. Lombard, M. Latash, & V. Zatsiorsky. Classics in Movement Sciences*, Chapter 10 (pp. 289–315). Champaign, IL: Human Kinetics Publ.
- Lombard, W.P. (1903). The action of two-joint muscles. *American Physical Education Review*, *8*, 141–145.
- McLaughlin, T.M., Lardner, T.J., & Dillman, C.J. (1978). Kinetics of the parallel squat. *Research Quarterly*, *49*, 175–179.
- Molbeck, S. (1965). On the paradoxical effect of some two-joint muscles. *Acta Morphologica Neerlandico-Scandinavica*, *6*, 171–176.
- Nagano, A., Ishige, Y., & Fukashiro, S. (1998). Comparison of new approaches to estimate mechanical output of individual joints in vertical jumps. *Journal of Biomechanics*, *31*, 951–955.
- Pandy, M.G., & Zajac, F.E. (1991). Optimal muscular coordination strategies for jumping. *Journal of Biomechanics*, *24*, 1–10.
- Prilutsky, B.U., & Zatsiorsky, V.M. (1994). Tendon action of two-joint muscles: Transfer of mechanical energy between joints during jumping, landing and running. *Journal of Biomechanics*, *27*, 25–34.
- Plagenhoef, S. (1971). *Patterns of human motion—A cinematographic analysis*. Englewood Cliffs, NJ: Prentice-Hall.
- Robertson, D.G.E., Stohart, J.P., & Wilson, J.M. (1988). *Electromyographic and impulse analysis of ergometer rowing. Biomechanics XI-B* (pp. 869–873). Amsterdam: Free University Press.
- Robertson, D.G.E., & Winter, D.A. (1980). Mechanical energy generation, absorption and transfer amongst segments during walking. *Journal of Biomechanics*, *13*, 845–854.
- Simonsen, E.B., Thomsen, L., & Klausen, K. (1985). Activity of mono- and biarticular leg muscles during sprint running. *European Journal of Applied Physiology*, *54*, 524–532.
- Van Ingen Schenau, G.J. (1984). An alternative view of the concept of utilization of elastic energy in human movement. *Human Movement Science*, *3*, 301–336.
- Van Soest, A.J., Schwab, A.L., Bobbert, M.F., & Van Ingen Schenau, G.J. (1993). The influence of the biarticularity of the gastrocnemius on vertical-jumping achievement. *Journal of Biomechanics*, *26*, 1–8.
- Winter, D.A. (1990). *Biomechanics and motor control of human movement* (2nd ed.). Toronto: John Wiley & Sons.
- Winter, D.A., Fuglevand, A.J., & Archer, S.E. (1994). Cross-talk in surface electromyography: Theoretical and practical estimates. *Journal of Electromyography and Kinesiology*, *4*, 15–26.
- Winter, D.A., & Robertson, D.G.E. (1978). Joint torque and energy patterns in normal gait. *Biological Cybernetics*, *29*, 137–142.
- Wilson, J.M., & Robertson, D.G.E. (1988). Analysis of biomechanical principles in weighted deep-knee bends. *Proceedings: Fifth Biennial Conference and Symposium of Canadian Society for Biomechanics*. London: Spodym Publishers. pp.174-175.
- Yang, J.F., & Winter, D.A. (1984). Electromyographic amplitude normalization methods: Improving their sensitivity as diagnostic tools in gait analysis. *Archives of Physical Medicine and Rehabilitation*, *65*, 517–521.
- Zajac, F.E. (1993). Muscle coordination of movement: A perspective. *Journal of Biomechanics*, *26*(Suppl. 1), 109–204.