

Muscle coordination and function during cutting movements

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ABSTRACT

NEPTUNE, R. R., I. C. WRIGHT, and A. J. VAN DEN BOGERT. Muscle coordination and function during cutting movements. *Med. Sci. Sports Exerc.*, Vol. 31, No. 2, pp. 294-302, 1999. **Purpose:** The objectives of this study were to: 1) establish a database of kinematic and EMG data during cutting movements, 2) describe normal muscle function and coordination of 12 lower extremity muscles during cutting movements susceptible to ankle sprains, and 3) identify potential muscle coordination deficiencies that may lead to ankle sprain injuries. **Methods:** Kinematic, EMG, and GRF data were collected from 10 recreationally active male subjects during both a side-shuffle and v-cut movement. **Results:** The data showed that muscles functioned similarly during both movements. The primary function of the hip and knee extensors was to decelerate the center-of-mass during landing and to provide propulsion during toe-off. The hip add/abductors functioned primarily to stabilize the hip rather than provide mechanical power. The ankle plantar flexors functioned to provide propulsion during toe-off, and the gastrocnemius had an additional burst of activity to plantarflex the foot before touchdown during the side-shuffle to help absorb the impact. The tibialis anterior functioned differently during each movement: to dorsiflex and supinate the foot after toe-off in preparation for the next step cycle during the side-shuffle and to dorsiflex the foot before impact to provide the heel-down landing and ankle stability in the stance phase during the v-cut. **Conclusions:** The muscles crossing the ankle joint, especially the tibialis anterior and peroneus longus, may play an important role to prevent ankle sprain injuries. Both muscles provided stability about the subtalar joint by preventing excessive joint rotations. Future theoretical studies with forward dynamic simulations incorporating individual muscle actuators are needed to quantify the segment accelerations induced by active muscles which may prevent or lead to ankle sprain injuries. **Key Words:** ELECTROMYOGRAPHY, HUMAN MOVEMENT, ANKLE SPRAINS

Ankle sprains are arguably the most common injury in sport (14) and can lead to significant impairment characterized by functional instability of the ankle joint (28). It is estimated that between 14% and 17% of all sport injuries are ankle sprains (7,14). Several treatments have been shown to reduce the incidence of ankle sprains, including footwear, taping, and bracing (8,21,23). Coordination training has also been used to restore functional stability by strengthening the muscles crossing the joint. Prospective studies have shown coordination training reduced functional instability after ankle sprains (6) and reduced the occurrence of further sprains independent of sprain history (25). Although coordination training has been shown to reduce the incidence of ankle sprains, the mechanism by which this treatment reduces the occurrence of

ankle sprains is not well understood because of a lack of data regarding muscle activation and muscle function during these movements.

Ankle sprains often occur during cutting-type movements (7). Several studies have investigated cutting-type movements kinematically with video and goniometer data to examine mechanisms of the ACL rupture (2), but these studies did not include EMG data to examine individual muscle coordination nor examine the data in the context of ankle sprains. Previous ankle studies have concentrated primarily on EMG activity of muscles crossing the ankle joint (13). But recent studies have indicated that muscles crossing the hip and knee joints may play an important role in stabilizing the ankle joint (1,18). To date, no study has combined entire lower extremity kinematic and EMG data to study mechanisms leading to ankle sprains. Considering the dynamic coupling between segments of the lower extremity, an analysis of the entire lower extremity including kinematic and EMG data would provide the data necessary to understand basic muscle function and coordination principles during movements susceptible to ankle sprains. A

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better understanding of these principles may provide insight into mechanisms that lead to ankle sprain injuries and provide the foundation for developing rehabilitation protocols.

Therefore, the objectives of this study were three-fold. The first objective was to establish a database of kinematic and EMG data to provide a foundation for future experimental and theoretical studies investigating muscle coordination and function during cutting movements. The second objective was to combine the kinematic and EMG data to describe normal muscle function and coordination during these movements. The third objective was to identify potential muscle coordination deficiencies and mechanisms which may lead to injuries.

METHODS

Ten recreationally active male subjects without a history of chronic ankle sprains (height = 177.2 ± 11.5 cm; weight = 73.3 ± 13.0 kg, age = 23.4 ± 2.3 yr) volunteered for participation in this study. Informed consent was obtained before the data collection. Data were collected during two different movements, a side-shuffle and a 45° forward v-cut. The order of the movements was randomly assigned to control for fatigue. The side-shuffle commenced with the subjects in a crouched position to the left of the force platform. Then, the subjects shuffled to their right twice, hitting the force platform with their right leg on the second shuffle and returning to the left. The subjects were instructed to perform the movement as quickly as possible. The 45° forward v-cut movement required the subjects to run straight forward with their right leg contacting the center of the force platform. Then the subjects cut to their left toward a target oriented at 45° . Running speed was controlled at 4.0 ± 0.4 m·s⁻¹ throughout the movement. The subjects were given as many practice runs as necessary to assure they felt comfortable with the movements and that they were consistently hitting the center of the force platform with their right foot.

EMG data were collected from the right soleus (SOL), medial gastrocnemius (GAS), tibialis anterior (TA), peroneus longus (PL), vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), medial hamstring (SM), biceps femoris (BF), gluteus maximus (GMAX), gluteus medius (GMED), and adductor magnus (AM) using pairs of surface electrodes (3 cm center-to-center) (Biovision, Wehrheim, Germany). Electrode placements were determined based on the work of Delagi and Perotto (3). The skin was shaved and cleaned with isopropyl alcohol to reduce the source impedance. The EMG signals were preamplified and sampled at 2400 Hz. The raw EMG data were bandpass filtered with cut-off frequencies of 30 and 1000 Hz with a common mode rejection ratio of 120 dB. Then, the data were full-wave rectified, smoothed using a root-mean-square (RMS) algorithm with a 40 ms moving rectangular window, and normalized to the maximum value achieved during both movements for each muscle using custom-written software. Because of hardware limitations, two sets of six electrode placements were collected independently. Five trials were

collected for each electrode set for a total of 10 trials during each movement.

The EMG data were further processed to compute muscle excitation burst onset and offset (16). The burst onset and offset timing were identified using an automated waveform processing program (Datapac III, RUN Technologies, Laguna Hills, CA). The criteria for the onset and offset times were based on a minimum threshold of 3 standard deviations of the muscle's inactive baseline and a minimum burst duration of 50 ms. Results were then examined interactively on a cycle-by-cycle basis and the threshold was increased when necessary to identify the burst onset and offset. The onset and offset values were computed on a trial-by-trial basis and averaged for each subject, and then averaged across subjects.

Ground reaction force (GRF) data were collected simultaneously with the EMG data at 2400 Hz using a force platform (Kistler Biomechanics, Switzerland). The heel-strike and toe-off times were identified from the GRF data when the vertical force exceeded and fell below 20 N, respectively. All muscle EMG data were time normalized relative to the stance phase duration (heel-strike to toe-off).

Lower extremity joint kinematics were determined using a high-speed video analysis system (Motion Analysis Corp., Santa Rosa, CA). Three retroreflective markers were placed on each segment of the right leg and pelvis (Fig. 1). Limb coordinate systems were defined relative to these markers using a standing neutral trial. The three-dimensional marker coordinate time histories were low-pass filtered using a quintic spline (GCVSPL; 27) with a cut-off frequency of 10 Hz. Limb segment orientations were reconstructed from the smoothed marker positions using the method of Soderkvist and Wedin (24). Hip and knee joint angles were then determined using the joint coordinate system of Grood and Suntay (9), and ankle joint angles were determined using the joint coordinate system of Inman (11).

RESULTS

EMG data. The subjects performed the side-shuffle movement with an average time of 413 ± 60 ms. The EMG patterns for the side-shuffle were consistent across subjects in both timing and magnitude. EMG patterns from a typical subject were presented in Figure 2. During the side-shuffle movement, the hip and knee extensors GMAX, RF, VM, and VL all exhibited a distinct single burst pattern with the burst onset before impact and offset before toe-off (Table 1). Similarly, the knee flexors BF and SM exhibited a burst of activity before impact but then remained relatively constant throughout the stance phase. Both GMED and AM displayed similar single burst patterns with a gradual onset before impact and gradual offset before toe-off. Different burst patterns were evident in the muscles crossing the ankle joint. MG exhibited a two-burst pattern with the first burst commencing before impact and the second before toe-off, whereas PL and SOL exhibited a single burst pattern. The TA pattern had the greatest variability across subjects with some subjects exhibiting a single burst pattern while others

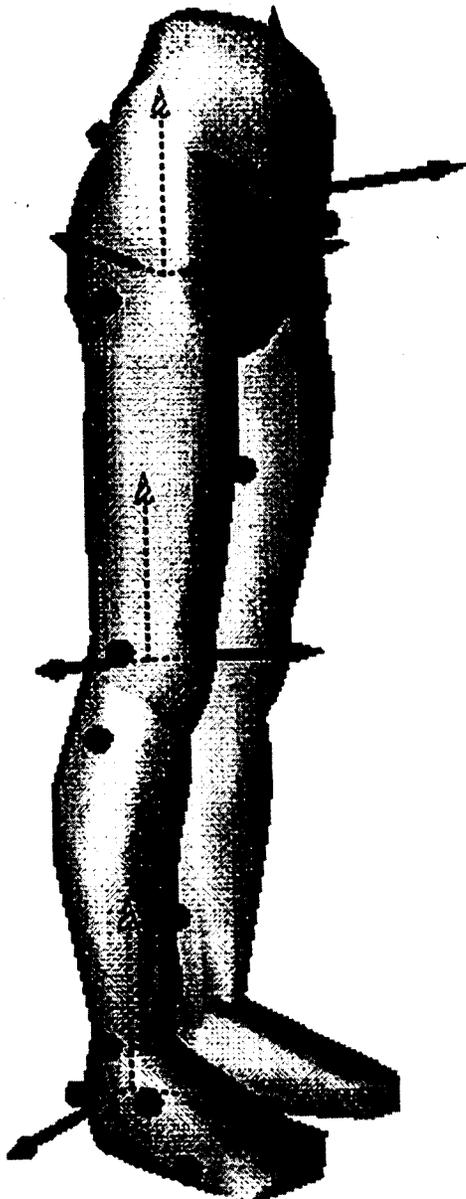


Figure 1—Experimental retroreflective marker placement on the lower extremity.

had a two-burst pattern. Some subjects exhibited a burst of activity before impact followed by a second burst which peaked after toe-off. For the subjects with the single burst pattern, the burst occurred near toe-off.

The subjects performed the v-cut movement with an average time of 294 ± 34 ms. Similar burst patterns were observed during the v-cut movement with more intersubject variability than the side-shuffle movement (Fig. 3, Table 1). The hip and knee extensors GMAX, RF, VM, and VL and thigh abductor GMIN all exhibited a single burst pattern that peaked before the midstance with a gradual onset of activity. The VM peak occurred substantially earlier than the VL peak, although both muscles had similar onset and offset timing (Table 1). The knee flexors BF and SM exhibited a small burst of activity during impact with a primary burst occurring before toe-off. AM activity began before impact

and remained relatively constant throughout the entire stance phase. The plantarflexors GAS, SOL, and PL all exhibited a single burst of activity during the stance phase with the peak occurring just before toe-off, whereas the TA activity was very similar to the side-shuffle movement.

Specific burst onset and offset values for each muscle averaged across subjects were presented in Table 1 for both movements. In general, the excitation timing variability was greater for the v-cut than for the side-shuffle movement. GAS and VM had the least timing variability for the side-shuffle and v-cut, respectively, while SM and GMED had the largest variability for the side-shuffle and v-cut, respectively. The TA onset variability was low during both movements.

Kinematic data. The kinematic data were similar in both magnitude and pattern across subjects during both movements. Figures 4 and 5 show typical joint rotations for the subject discussed above during the side-shuffle and v-cut movements, respectively. Note, because of field of view limitations in our video analysis system, data were only presented during the stance phase. Distinctive differences between the two movements were observed at the ankle joint. Just before impact, the magnitude of supination was similar between the two movements but peaked at 45° near 30% of the stance phase during the side-shuffle, whereas it remained relatively constant throughout the v-cut at 20° . During both movements, the amount of supination decreased rapidly just before toe-off. Similar patterns were observed during both movements for the ankle plantar flexion. Peak dorsiflexion occurred near midstance and then plantar flexed near toe-off.

Both the range and temporal timing of the knee flexion/extension were similar for both movements with peak knee flexion occurring at the midstance (Figs. 4 and 5). Distinct differences in both pattern and magnitude were seen in the knee internal/external rotation. The knee was externally rotated before impact during the shuffle movement and then internally rotated at impact to its neutral position until about 75% of the stance phase and then began to externally rotate again at toe-off. During the v-cut, before impact the knee was in a neutral position and internally rotated at impact but remained relatively neutral throughout the stance phase. The point of maximum external tibial rotation occurred at toe-off when the leg was in its most extended position (Fig. 5).

Differences were also observed in the hip flexion/extension and hip adduction/abduction (Figs. 4 and 5). During the v-cut, the hip was flexed near 40° at impact and then systematically extended throughout the stance phase. But in the side-shuffle, the hip was extending at impact, reached peak flexion at midstance and then extended until toe-off. Similar differences between the two movements were observed in the hip adduction/abduction. During both movements, similar patterns were observed in the hip internal/external rotation with the thigh externally rotated throughout the entire movement with the minimum occurring just after impact.

All data, including the EMG and kinematic data, can be downloaded from the International Society of Biomechanics web site (<http://isb.ri.ccf.org/data/rnn>).

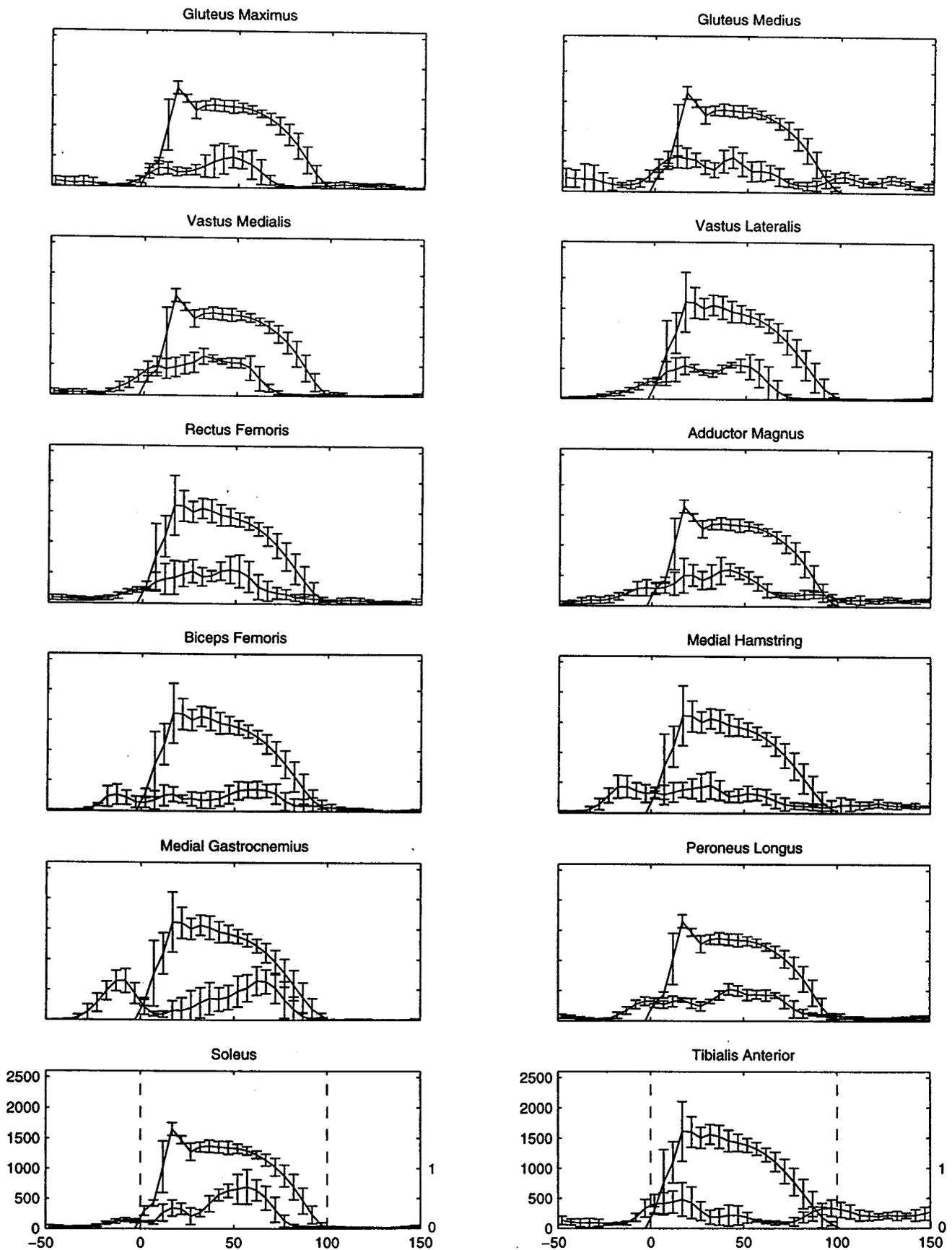


Figure 2—Normalized EMG patterns of the 12 lower extremity muscles for a typical subject during the side-shuffle movement. The average stance phase time was 0.329 and 0.266 s for the side-shuffle and v-cut movements, respectively. The horizontal time scale is normalized to the stance phase duration from impact (0%) to toe-off (100%). The EMG data are normalized to the maximum value achieved during both movements. The units for the ground reaction force data are Newtons.

TABLE 1. Muscle EMG onset and offset timing for both movements average across subjects.

Muscle	Side-Shuffle				V-Cut			
	Onset		Offset		Onset		Offset	
	Average	SD	Average	SD	Average	SD	Average	SD
GMAX	-15.4	14.5	81.4	8.0	-58.7	15.3	79.3	12.1
GMED	-20.9	7.5	80.0	18.2	-52.2	18.5	107.5	32.6
RF	-25.2	9.1	87.6	9.1	-25.9	8.8	79.8	15.0
VL	-34.4	11.7	81.6	5.7	-36.3	13.7	78.1	13.2
VM	-33.6	10.5	82.0	5.8	-41.3	9.8	81.8	12.4
AM	-38.0	14.2	99.2	13.0	-43.6	9.5	89.7	32.7
BF	-33.9	6.1	97.0	12.3	-48.3	16.1	90.4	11.0
SM	-33.4	5.7	93.7	28.0	-62.6	15.9	89.9	16.9
GAS	-37.7	6.4	88.9	2.8	-43.5	20.2	90.5	9.0
SOL	-30.8	13.2	86.4	4.3	-32.0	18.1	86.4	5.8
PL	-35.1	15.7	97.1	10.4	-48.8	18.6	94.0	9.5
TA	80.5	3.7	*	*	74.3	9.4	*	*

Units are in percent stance phase. Note that the TA offset occurred well after toe-off in 8 of the 10 subjects, so only the onset value is presented for those subjects.

DISCUSSION

The objectives of this study were three-fold. The first objective was to establish a database of kinematic and EMG data for future experimental and theoretical studies investigating muscle coordination and function during cutting movements. The second objective was to describe normal muscle function and coordination of 12 lower extremity muscles during cutting-type movements susceptible to ankle sprains. The third objective was to identify potential muscle coordination deficiencies which may lead to ankle sprain injuries. To achieve this goal, kinematic, EMG and GRF data were collected from 10 male subjects during both a side-shuffle and v-cut movement.

Before the assessment of muscle function can be made, two potential limitations of the study must be considered. First, data were not collected from the tibialis posterior muscle which is an important invertor muscle. Studies have suggested that early tibialis posterior activity may be related to ankle sprains by excessively inverting the foot (22). Measurement of tibialis posterior muscle activity would require indwelling electrodes which was not feasible in this study, but the exclusion of this muscle should not affect the discussion of potential injury mechanisms. Secondly, the methodology used to identify the EMG onset and offset timing warrants discussion. The method used in this study utilized an automated waveform processing program combined with an interactive visual inspection as described by Neptune et al. (16). The onset/offset burst threshold was systematically increased to identify the burst onset and offset when the burst off duration did not fall within 3 standard deviations of the resting baseline. This analysis was repeated with a different analyst and the results were found to be consistent. No other method was found to provide reliable and satisfactory results.

The assessment of muscle function was made by relating the EMG activity to the corresponding joint kinematics. When comparing EMG to joint kinematics, keep in mind that EMG precedes muscle force development because of the activation dynamics associated with muscle force development. This electromechanical delay is considered to be between 20 and 100 ms (26).

The results of the EMG and kinematic data showed that the primary function of the vasti muscle group during both

the side-cut and v-cut movements was to eccentrically decelerate the downward motion of the body's center of mass after impact, stabilize the knee, and extend the knee during the propulsion phase (>50% of the stance phase). The peak vasti activity occurred at peak knee flexion angle for both movements. This combination of joint kinematics and muscle activity creates a stretch-shortening cycle that has been observed in many other movements and may be used to enhance muscle force development to increase muscle power during the propulsion phase (10). The difference in peak EMG timing between VM and VL during the v-cut movement was consistent with previous studies on running that have suggested the timing difference is related to patellar tracking and stabilization (15). The biarticular RF acts primarily as a knee extensor, not as a hip flexor, because the hip is beginning to extend near the peak RF activity. This indicates RF may also be transferring power from the hip extensors to the knee joint (12).

In both movements, the primary function of the hamstring muscles BF and SM appeared to eccentrically decelerate the center of mass during impact as a hip extensor and provide acceleration during the propulsion phase. The primary BF burst occurred at the transition from knee flexion to extension at the same point where the hip began to extend (Figs. 4 and 5). The hamstring muscles can also contribute to the amount of tibia rotation. SM, with its medial insertion, can prevent excessive external rotation, whereas BF, with its lateral insertion, can prevent excessive internal rotation. Although it is difficult to speculate what contribution if any the BF and SM muscles have to the observed tibial external and internal rotations, respectively, in this study, previous studies have suggested the hamstring muscles may play an important role in preventing excessive tibial rotations (17), which can lead to ankle sprain injuries.

Both GMED and AM exhibited nearly constant EMG activity, and the constant hip joint adduction/abduction angle during both movements suggests the primary function of these muscles is to isometrically stabilize the hip rather than produce mechanical power. Similar to the quadriceps muscle group, onset of GMAX activity occurred before impact to eccentrically decelerate the center of mass and then peaked at midstance to concentrically provide propulsion for both movements. The onset of muscle activity occurred

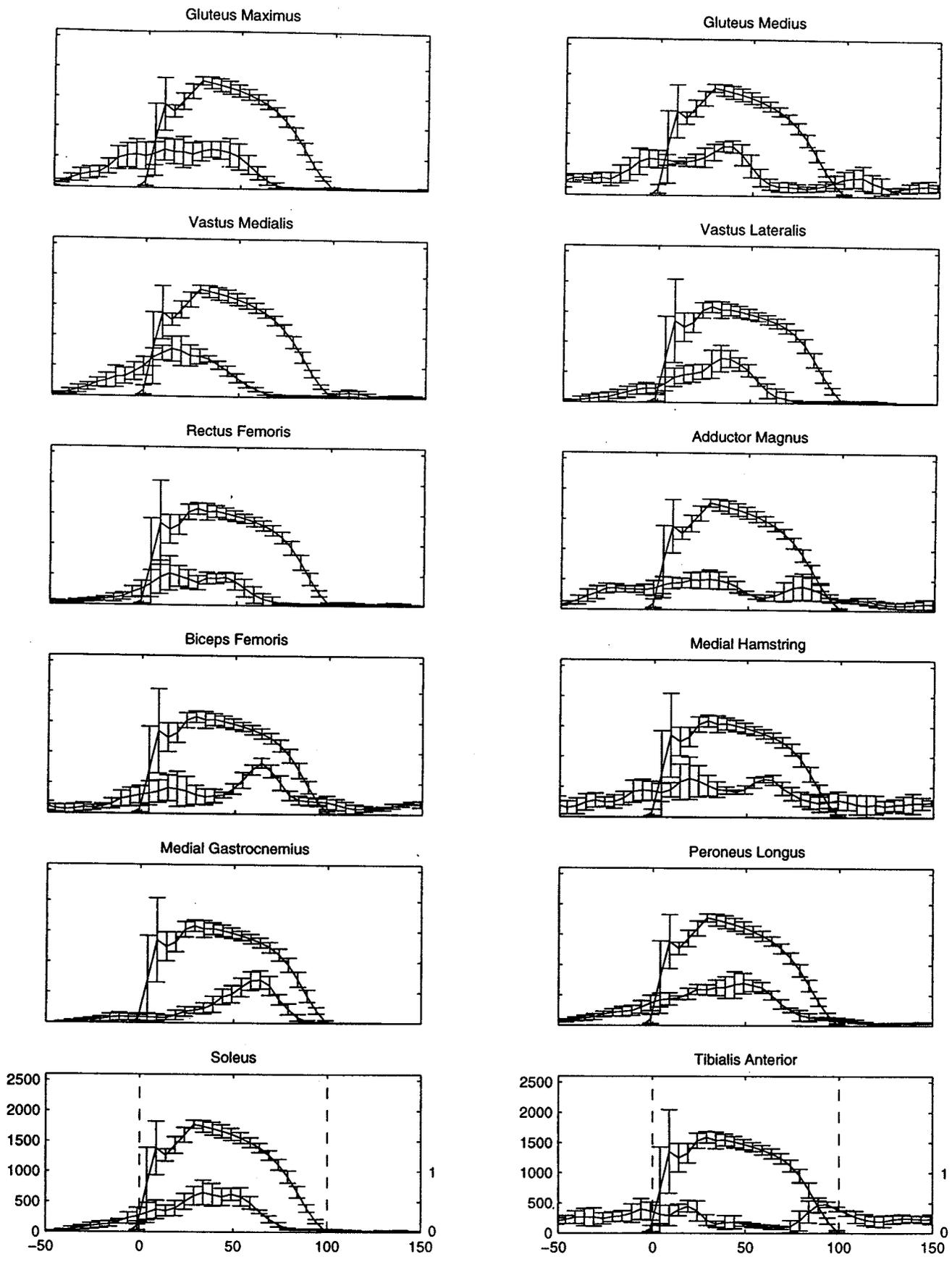


Figure 3—Normalized EMG patterns of the 12 lower extremity muscles for a typical subject during the v-cut movement. Note, the time scale is different between the side-shuffle and v-cut movements.

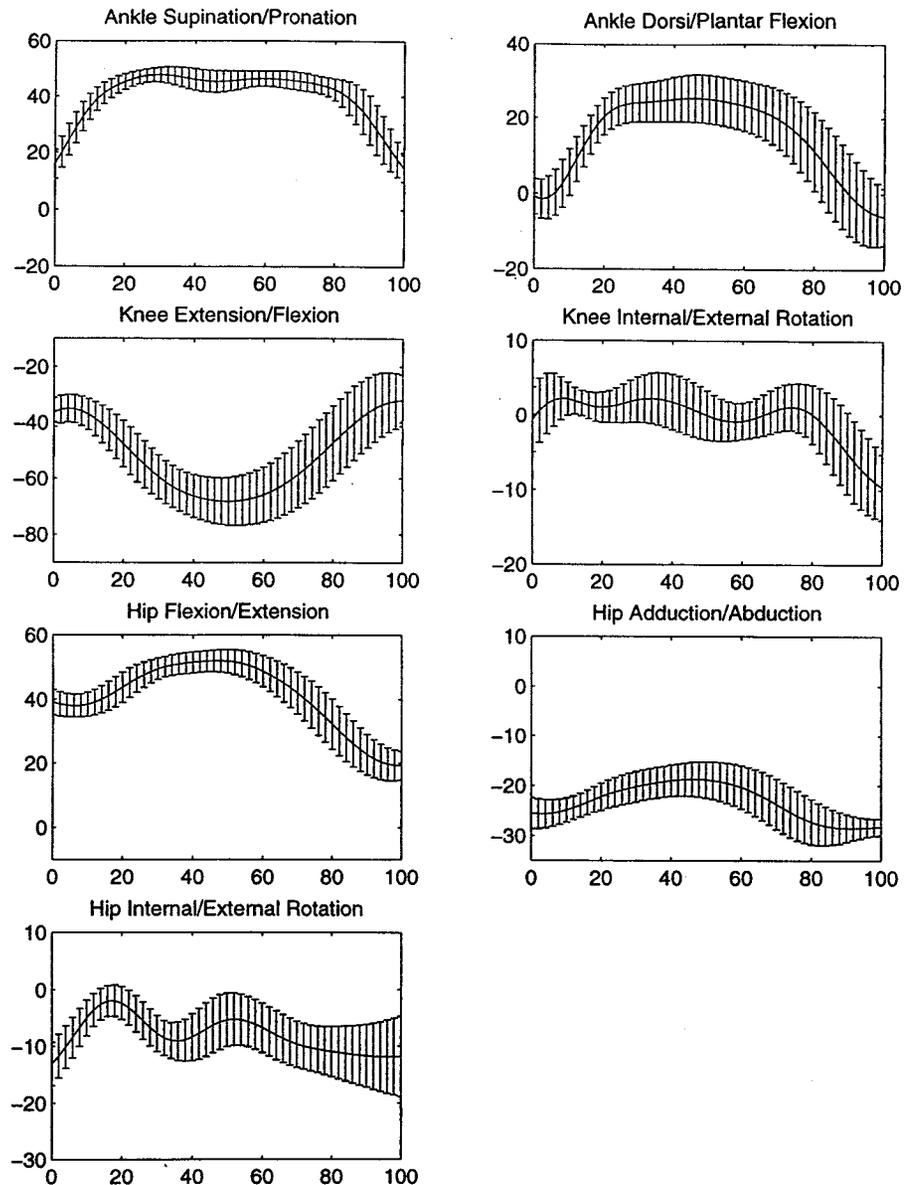


Figure 4—Lower extremity kinematic data for a typical subject during the side-shuffle movement. Units are in degrees. The horizontal time scale is normalized to the stance phase duration from impact to toe-off. Note, the horizontal scale is the same for both the kinematic and EMG data, but the EMG data is plotted for a longer duration. Positive angles indicate ankle supination, dorsiflexion, knee extension, internal rotation, hip flexion, adduction, and internal rotation, respectively.

much earlier during the v-cut movement to possibly emphasize impact absorption, hip stabilization, and initiate a stretch-shortening cycle to enhance propulsion.

The plantar flexor muscles GAS, SOL, and PL all exhibited similar muscle activity in both movements except for the GAS burst of activity before impact during the shuffle movement. Examination of the shuffle ankle kinematic data indicated that this burst of activity occurred to plantar flex the foot before impact and subsequently allowing the eccentric action of these muscles to absorb the impact and reduce joint loading. PL was also active before impact, which may also contribute to this function. Then, the concentric action of these three muscles appear to provide propulsion before toe-off since plantar flexion corresponds with EMG activity of these muscles, as well as GAS transferring knee power to the ankle joint (12). These results disagree with Reber et al. (19), who suggested the posterior muscles of the ankle joint only provide dynamic stability to

the ankle joint and not push off. Differences in identified muscle function between the two studies were most likely related to differences in movements and that Reber et al. (19) did not consider an electromechanical delay in their analysis.

PL appears not only to contribute to ankle plantar flexion but also provides stability to the subtalar joint. The PL activity starts before impact and rises more abruptly during the side-shuffle, which decelerates the rapid supination after touchdown. The activity remains high, whereas supination remains relatively constant during the midstance, indicating that the muscle stabilizes the subtalar joint. Previous studies examining PL activity in relation to ankle sprain injuries have focused on its protective reflex response during rapid supination movements (13). But during the movements in this study, PL is clearly activated before impact as a protective mechanism to balance the GAS (supination) activity. These results further support that PL is a potentially critical muscle in preventing ankle sprain injuries.

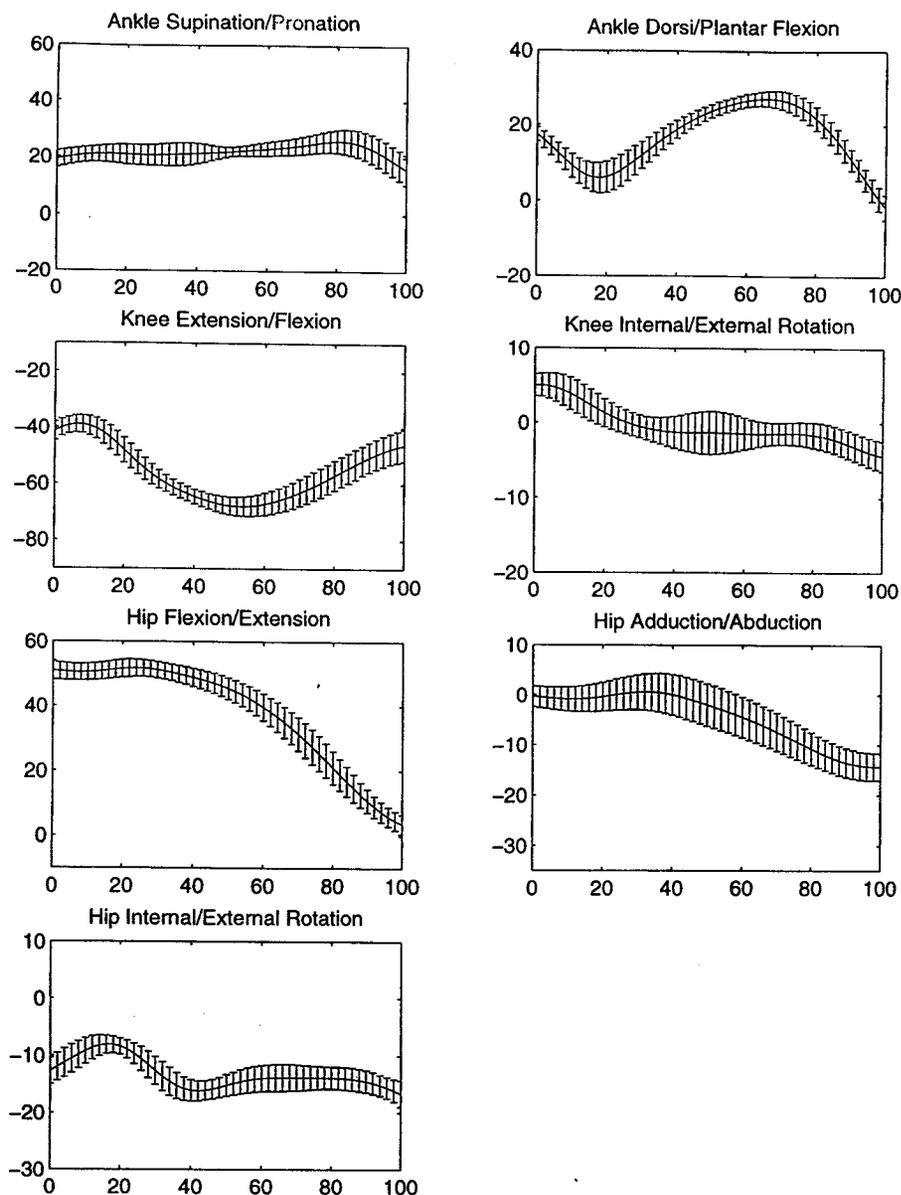


Figure 5—Lower extremity kinematic data for a typical subject during the v-cut movement.

Finally, the function of TA appears to be different for each movement. During the side-shuffle, TA functions primarily to dorsiflex and supinate the foot after toe-off in preparation for the next step cycle (Fig. 4). But in the v-cut movement, the TA activity was nearly constant throughout the entire movement to dorsiflex the foot before impact thus providing the heel-down landing and ankle stability during the stance phase (Fig. 3).

TA is an important muscle in preventing ankle sprains, especially in the v-cut movement, by impeding excessive ankle plantar flexion, which has been shown as a primary mechanism in ankle sprain injuries (4). TA activity before impact may also prestretch the SOL and GAS muscles to enhance ankle plantar flexion and dorsiflexion deceleration capacity to reduce impact joint loading (5). Reber et al. (19) showed that TA had the highest rate of sustained muscle activity of all the muscles they tested crossing the ankle joint, indicating fatigue may play an important role in ankle injuries by altering the muscle timing.

Although TA provides ankle stability by co-contracting with the plantarflexors and PL, the TA medial insertion point from the subtalar axis provides supination. Excessive foot supination at impact caused by an imbalance between inverter and everter activity has also been suggested as an ankle sprain mechanism (20). Both SOL and TA activity can potentially oversupinate the foot before impact, leaving the ankle vulnerable to injury. However, examination of the EMG data during the v-cut movement of those muscles crossing the ankle joint showed that only TA is active before impact, again exemplifying the critical role of TA in ankle joint stability.

CONCLUSIONS

Based on experimental measurements such as those presented in this paper, it is difficult to fully understand the mechanisms behind the segment accelerations active mus-

cles induce that may prevent or lead to injuries. This information may only be obtained using forward dynamic simulation studies incorporating individual muscle actuators to increase our understanding of muscle function and coordination (29). The advantage of such theoretical simulation studies is that initial conditions and kinematics throughout the movement can be carefully controlled to investigate the effect of different muscle coordination strategies on joint loading and kinematics.

This paper has provided the kinematic and EMG data necessary to design theoretical and experimental studies to further investigate mechanisms behind ankle sprain injuries.

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Future studies need to include all major muscle groups of the lower extremity because of the coupled dynamics within all the body segments. Muscles crossing the hip and knee joints can have a significant effect on ankle joint kinetics and kinematics (17,30).

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