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THE ROLE OF ANKLE PLANTAR FLEXOR MUSCLE WORK DURING WALKING

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ABSTRACT. Impaired ankle plantar flexor (APF) function is a frequent cause of gait limitations, but the role of the APF in the forward propulsion of the body remains controversial. To better understand both the direct and indirect effects of the APF during push-off and through advancement of the leg, mechanical work and inverse dynamic analyses were performed on 8 normal subjects during level walking. During push-off, 23.1 joules (J) of energy were generated, primarily by the APF, but only 4.2 J of this energy is transferred into the trunk. Ankle plantar flexor work is primarily used to accelerate the leg into swing. Most of the energy, 18.6 J, is recovered by transfer into the trunk at the end of swing. The timing of the energy transfers relative to the trunk motion imply that the APF contributes to the forward kinetic energy of the trunk but that other mechanisms likely account for the work used to raise the trunk against gravity.

Key words: biomechanics, energy transfer, gait, plantar flexor muscle.

INTRODUCTION

Impaired or absent function of the ankle plantar flexors (APF) is a frequent sequela of stroke, brain injury, peripheral neuropathies and lower extremity amputation. Because of the common use of orthotic and prosthetic devices to substitute for APF loss or weakness, there is a need to clearly understand the role of these muscles during walking. This will allow more rational decisions about rehabilitation interventions and better defined, realistic expectations for functional improvements in these patients.

Electromyographic (EMG) recordings, combined with temporal gait data, have enhanced our understanding of APF function (16–18, 24). The APF muscles become active after heelstrike at a moderate level which continues through midstance, when increased EMG activity occurs as the foot begins to plantar flex. There is general agreement that during midstance, the APF muscles contract eccentrically and contribute to knee and ankle stability and to restraint of the forward rotation of the tibia. At approximately 40% of the stride cycle, APF muscle activity becomes concentric and reaches a peak at 40–50% (7, 28) of the stride cycle. The cessation of EMG activity has been variably reported to occur just after contralateral heelstrike (7, 14) or at the end of stance phase (1, 28).

It is during late stance that controversy exists over the biomechanical role of the APF. Three differing conceptual frameworks regarding APF function have been advanced by various researchers: (1) the APF restrains the forward movement of the trunk over the ankle joint but does not contribute to forward propulsion, (2) it accelerates the leg into swing phase, and (3) actively propels the trunk upward and forward.

Several investigations have concluded that the APF do not contribute to propulsion of the body (16, 18, 23, 25), leading Perry to avoid the term “push-off”. She proposes that the late peak of the ground reaction force is the result of leverage from body alignment rather than an active downward thrust (18), implying that forward inertia is sufficient to move the body forward during the push-off period. Both Simon et al. (23) and Sutherland et al. (25) studied APF function using tibial nerve blocks and came to the similar conclusion that their primary role is to restrain the motion of the trunk as it rotates over the stance phase leg. In addition, they proposed that during late single limb support, APF contraction lengthens the limb helping to prevent excessive drop in the vertical position of the trunk but does not actively propel the body forward. A second argument used to question a direct role by the APF in forward propulsion of the trunk comes from the observation that the EMG activity of the APF usually stops before a significant amount of mechanical work is generated by these muscles (7). However, this can be largely attributed to the delay between the EMG activity and the mechanical output of the muscle.

Evidence of a more direct role for the ankle plantar flexors in forward propulsion or “push-off” comes from several sources. A direct effect of APF on trunk acceleration is suggested by the observation (7) that the triceps surae peak EMG activity at push-off coincides with the most important increase in total mechanical energy of the body. The orientation of the ground reaction force vector is upward and forward during the push-off phase of the stride cycle, also suggesting a propulsive function of the APF (6). Using an inverse dynamics technique, Winter (26) estimated the mechanical energy generation and absorption characteristics of the APF. This study demonstrated late stance positive work generation by the ankle plantar flexors that increases in magnitude with faster walking and coincides with the second vertical peak in the ground reaction force profile. Winter concluded that this power burst from the APF was major "new energy that propels the body forward" and hypothesized that APF work increased the potential and kinetic energy of the leg, thigh and upper body. A less direct effect on propulsion comes from studies (3, 5, 29) that concluded that the primary role of the APF was to increase the energy of the leg as it is accelerated into swing and only a small amount is transferred to the trunk during push-off.

The lack of a clear consensus regarding the role of the ankle plantar flexors exists for several reasons. The first is that the APF likely has several non-exclusive functions during gait. The role of the APF in controlling the forward progression of the trunk during single limb support does not preclude a less direct effect on body propulsion through an effect on leg acceleration. Secondly, with the exception of limited studies using power flow analysis, investigations of APF function have tended to focus on limited periods of the stride cycle, mainly single limb support. This ignores the important period of energy generation by the APF during double limb support and transfers of energy that occur between the leg and trunk during swing phase. This study was undertaken in an attempt to further clarify the role of the APF by including both direct and indirect effects on leg and trunk propulsion. This study builds on previous work (26, 29) by combining power output analysis of the muscle groups of the leg, energy transfers across the hip joint, and segmental energy analysis to allow improved qualitative insights and quantification of the sources of work needed to propel the trunk and their relationship to APF action.

METHODS

Subjects

Eight normal subjects, 7 males and 1 female, were studied. The subjects ranged in age from 25 to 38 years and their mean mass was 84.9 kg (SD 9.9). No attempt was made to control for footwear. All subjects used their usual footwear, which was either athletic shoes or flexible soled dress shoes.

Equipment

A force platform was used to collect ground reaction forces at a sampling rate of 480 Hz. Joint kinematic data were collected by a video system at a sampling rate of 60 Hz and saved to videotape for further analysis. Synchronization was obtained between the force plate data and the video data, using a light emitting diode that was triggered by foot contact with the force platform.

Data collection

Reflective markers were placed on the following anatomical landmarks: fifth metatarso-phalangeal joint, heel, lateral malleolus (ankle), lateral femoral epicondyle (knee), greater trochanter (hip) and the vertebral body of C7. After a period of acclimatization each subject's self-selected walking speed was determined during level walking. The video camera was positioned perpendicular to the walkway at hip height, placed at a distance from the walkway to allow one complete stride (heelstrike to heelstrike of the leg under study) to be captured during each trial. Walking trials were collected from the right leg only, while the subjects walked at their self-selected walking speed. Walking speed was monitored during data collection using two infrared beam sensors spaced two meters apart centered about the force plate. Trials were rejected if the walking speed differed by more than 10% from the established self-selected walking speed. Force plate data and kinematic video data were obtained for at least three entire stride cycles.

Parameter calculation

The x- and y-coordinates of the joint markers were determined by digitizing the video image using a video motion analysis system (Peak Performance Technologies, Boulder, CO). The horizontal and vertical marker coordinates were filtered using a fourth order zero lag digital Butterworth filter with cut-off frequencies determined based on the method of Jackson (13). The cut-off frequencies ranged from 3 Hz for the hip and C7 x-coordinate to 6 Hz for the toe y-coordinate. Subsequent analysis of force and kinematic data was performed using a custom SuperScope II computer program (GW Instruments, Inc., Somerville, MA), running on an Apple Macintosh computer.

Body segment parameters were derived from Dempster's regression relationships as reported in Winter (27). Standard link segment kinetic analyses (6, 20) were used to calculate the vertical and horizontal joint forces, segmental center of mass moments and muscle and joint powers acting at the ankle, knee and hip joint. The net muscle moments were calculated by assuming equilibrium between the moments due to the vertical and horizontal joint forces and muscle moments and the product of the segment moment of inertia and angular acceleration. Muscle power was determined using the relationship:

$$P_{\mathrm{m}} = M * \omega,$$

where P_{m} is the net mechanical muscle power, M is the net moment and ω is the joint angular velocity. For the hip muscle power the thigh segmental angular velocity was used so that hip muscle power reflects the effect of hip muscles on thigh motion only.

The joint power was calculated from:

$$P_{\mathrm{j}} = F_{\mathrm{x}} * v_{\mathrm{x}} + F_{\mathrm{y}} * v_{\mathrm{y}},$$

where P_{j} represents the power delivered to or taken from a segment due to work done by joint reaction forces, F_{x} and F_{y}

are the joint reaction forces in the x and y direction, respectively, and v_x and v_y are the joint velocities.

The net muscle and joint powers were integrated to calculate the mechanical work done on a segment through muscle activity (W_m) or through inter-segmental energy transfer (W_j). Positive muscle and joint powers indicate that power is generated by the muscle or transferred to the segment and, if negative, power is absorbed by the muscle or transferred out of a segment.

Mechanical work was calculated based on the kinematics of the individual body segments. Segmental mechanical energies (E_s) were determined by summing each segment's potential energy, translational kinetic energy and rotational kinetic energy (27). The segments analyzed were the foot, shank, thigh, trunk and the total leg. The total leg segment includes the thigh, shank and foot segment.

The rate of change in mechanical energy over a period of time equals the amount of mechanical work done on a segment. A distinction was made between internal and external mechanical work (27). External work done on the segment was calculated under the assumption of complete exchange of energy within a segment and thus represents the minimal external work that must be done on the segment to produce the observed motion. The summation of the absolute changes in E_s between the N sample periods in the stride equals the amount of external work:

$$W_{\mathrm{ext,s}} = \sum_{i=1}^{N} \mid \Delta E_{\mathrm{s}} \mid .$$

Of special importance to understanding APF function is positive external work [$W_{\mathrm{ext(pos)}}$]. This is the subset of external work that includes only the external work needed to increase (but not decrease) segmental energy.

Joint and muscle powers and segment energy calculations were performed on the three individual trials for each subject, normalized for body mass, and then averaged. The reported work calculations [W_m, W_j, $W_{\mathrm{ext(pos)}}$] are based on the individual subject's power and segmental energy data, which were averaged to obtain population means and standard deviations. Several intervals of the stride cycle were selected for analysis based on their expected importance in understanding the effect of APF function on trunk propulsion. These included the period of positive power generation by the APF, termed the "push-off phase" (phase A2, Fig. 4), and the periods of energy transfer across the hip joint from the leg to the trunk designed as "swing deceleration" (phase J5, Fig. 3) and "early stance deceleration" (phase J1, Fig. 3).

Gait events are expressed as a percentage of the stride cycle. The units for power is watts (W) and work values are in joules (J). To allow for more convenient and intuitive understanding of the magnitude of work and power values, these are expressed as normalized values for a hypothetical 85 kg subject (the average mass of the subjects in the study).

RESULTS

The average walking speed for the subjects was 81 m/min (SD 8.4). Total stride time was 1.15 sec (SD 0.04) with stance phase lasting for 64% (SD 1.4) of the stride. The positive power generation phase of the APF ("push-off") began at 44% (SD 3) of the stride cycle. At this time, the contralateral leg is still in the terminal swing phase, which ends at 50% (SD 1) with contralateral heelstrike.

The summed total leg muscle power and the hip joint power are shown in Fig. 3. The individual muscle power curves for the ankle, knee and hip muscles are given in Fig. 4. Across the hip joint there are three outflow phases of energy transfer from the leg to the trunk. These are the periods of negative hip joint power as seen in Fig. 3 and include: (1) an early stance J1 phase that occurs during the first third of stance, (2) a small J3 outflow phase during push-off that corresponds to timing of the peak power output of the APF, and (3) the major outflow phase J5 that occurs as the swing leg is decelerated. Timing of the muscle and joint power phases is summarized in Table I. The results of the work calculations are summarized in Tables II and III.

During the push-off phase total leg energy increases by 28.7 J (SD 5.1) as the leg is accelerated forward and upward (Fig. 1). Two sources of energy contribute to the leg energy increase, leg muscle work and energy transfer across the hip. A net total of 23.1 J (SD 6.2) of muscle work is performed by the leg muscles. Two muscle groups generate positive work during this period: the APF produce 31.9 J (SD 4.7) and the hip flexors produce 9.2 J (SD 2.7) (Fig. 4). The difference between the net positive muscle work done for the leg as a whole and the summed positive work done by the APF and hip flexors is due primarily to 16.6 J (SD 5.1) of energy absorption by the knee extensors. During the push-off phase, energy is transferred across the hip joint in both directions (i.e. into and out of the trunk). At the peak of the APF power output, 4.2 J (SD 3.2) of work is transferred into the trunk during the J3 hip joint power phase. Preceding and following this burst of energy transfer into the trunk, energy leaves the trunk [6.3 J (SD 2.9)] and is transferred into the leg. Thus, during the push-off phase

Table I. *Timing of muscle and joint power phases*

	Start	End
Power phase*	% stride cycle (SD)	
A2—Concentric APF phase	44.3 (2.8)	62.2 (1.3)
J1—Early stance transfer into trunk	5.0 (3.9)	21.6 (2.6)
J3—Push-off transfer into trunk	49.9 (3.4)	56.8 (2.3)
J5—Swing deceleration transfer into trunk	73.0 (3.2)	100

* Phase designation refers to ankle muscle power outputs (A phases) and hip joint power powers outputs (J phases). See Figs 3 and 4.
APF: ankle plantar flexors.

Table II. *Energy changes and positive external work in trunk and leg segments*

	Push-off phase (A2)	Swing deceleration (J5)	Early stance deceleration (J1)
Net trunk energy change*	−1.7 J (7.2)	−3.3 J (5.3)	−3.4 J (6.0)
Trunk external work [$W_{ext(pos)}$]	5.6 J (5.2)	4.2 J (4.1)	2.5 J (1.7)
Net total leg energy change	28.7 J (5.1)	−26.8 J (6.3)	−6.2 J (2.2)
Total leg external work [$W_{ext(pos)}$]	29.7 J (5.4)	< 1	< 1

* Net energy values are differences in the total segment energy between the start and end of the phase.

Table III. *Muscle and joint work during phases of energy transfer into the trunk*

	Push-off (A2)	Swing deceleration (J5)	Early stance deceleration (J1)
Ankle positive	31.9 (4.7)	< 1	< 1
Ankle negative	< 1	< 1	−2.7 (1.5)
Knee positive			2.8 (1.6)
Knee negative	−16.6 (5.1)	−11.0 (2.1)	−3.5 (2.2)
Hip positive	9.2 (2.7)	1.6 (1.0)	2.2 (2.8)
Hip negative	−1.9 (1.06)	< 1	−1.1 (1.5)
Hip joint work: joules (SD)			
Positive (into leg)	6.3 (2.9)	< 1	< 1
Negative (into trunk)	−4.2 (3.2)	−18.6 (5.2)	−6.5 (3.9)

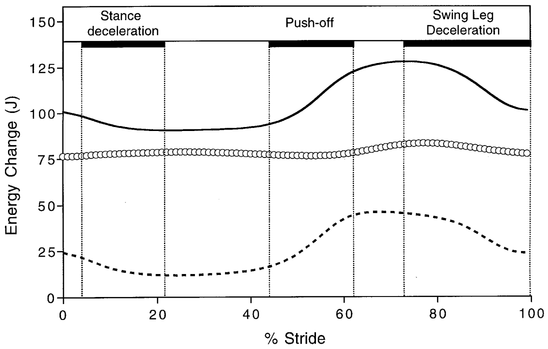

Fig. 1. Potential, kinetic and total leg energy levels for all subjects over a complete stride. Total leg energy (—), potential energy (-○-○-) and kinetic energy (- - -). In all illustrations, the vertical lines designate the start and stop of the stance deceleration or J1 phase, the pushoff or A2 phase and the swing deceleration or J5 phase.

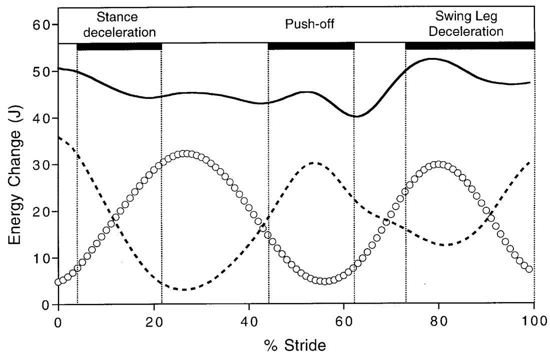

Fig. 2. Potential, kinetic and total trunk energy levels for all subjects over a complete stride. Total trunk energy (—), potential energy (-○-○-) and kinetic energy (- - -).

there is a net small energy transfer across the hip out of the trunk into the leg of 2.1 J. During the push-off phase the trunk energy level decreases by 1.7 J (SD 7.2), but 5.6 J (SD 5.2 J) of positive external work is needed due to oscillation in the total trunk energy level (Fig. 2). The individual components of the total trunk energy show a local minimum potential energy and a local maximum kinetic energy.

During the swing deceleration phase (phase J5, Fig. 3) the total leg energy decreases by 26.8 J (SD 6.3). While the leg is losing energy, this energy is available for other purposes. Coincident with the loss of swing leg energy is the transfer of 18.6 J (SD 5.2) of energy across the hip joint into the trunk. The remaining energy is absorbed by an eccentric contraction of the knee flexor muscles: −11.0 J (SD 2.1). Despite the transfer of more than 18 J of energy into the trunk, the trunk experiences a net loss of 3.3 J (SD 5.3) of energy between the beginning and end of the J5 phase. When the oscillation of the trunk is taken into account, 4.2 J (SD 4.1) of positive work must be done on the trunk during swing deceleration. The loss of leg energy continues into early stance phase reaching a baseline level at the end of the J1 phase (Fig. 1).

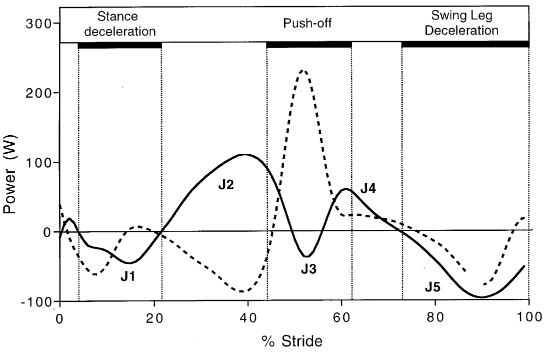

Fig. 3. Hip joint power output (—) and summed muscle power output of all leg muscles (- - -) during a complete stride. Positive muscle power indicate a concentric muscle contraction which generates work, negative muscle power occurs during eccentric contractions as the muscle absorbs energy. Positive hip joint power indicate energy is being transferred from the trunk into the leg while negative hip joint power indicates transfer from the leg into the trunk.

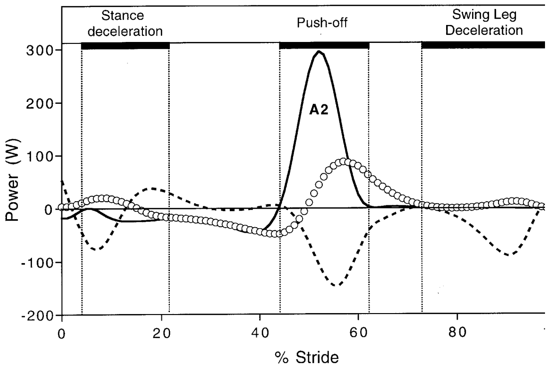

Fig. 4. Individual joint muscle power outputs during a complete stride. Ankle power (—), knee power (- - -) and hip power (-○-○-).

DISCUSSION

Understanding the function of the APF is essential in rehabilitation settings so that realistic expectations can be developed regarding the ability of orthotic and prosthetic devices to substitute for their loss or impaired function. Clinically, the emphasis in understanding the APF has been focused on their role in directly controlling and propelling the trunk forward during "push-off". Indeed, much of the apparent controversy over the role of the APF appears to originate from a failure to include both the direct, immediate effects of the APF and more indirect and less obvious effects via its influence on the acceleration of the leg prior to swing phase. Although mechanical work and energy analysis techniques cannot directly track the work done by the APF during push-off, by relating the timing and magnitude of the work produced by the APF with energy transfers across the hip and changes in the kinetic and potential energy levels of the leg and trunk, it is possible to make useful observations and gain qualitative and quantitative insights into the role of the APF in gait. This was the approach taken in this study.

The APF generate significant positive work only during "push-off", the phase of concentric contraction of the APF that begins during the end of single limb support and extends through the period of double limb support. Similar to other investigators (8, 20, 22, 28, 30), this study confirmed that during the push-off phase the APF muscles are the single most important source of positive muscle work, generating 31.9 J of work. A second source of significant positive muscle work during push-off is the hip flexor muscle group, which generates approximately 29% of the work (9.2 J) produced by the APF. During push-off, as these muscle groups perform work through concentric muscle contraction, the potential and kinetic energy of the leg increases substantially above its baseline level (Fig. 1). The close temporal synchrony between the work done by these muscle groups and the rapid increase in leg energy supports the concept that the most important, immediate, and direct action of the APF is to accelerate the leg into swing phase. A similar relationship between APF muscle work and leg energy has been noted by Elftman (6) and Winter et al. (29, 31). Further analysis by these investigators has shown that the increase in leg energy is a result of APF muscle work as it is transferred from the foot to the shank and thigh.

The direct contribution of the APF to increasing trunk energy during push-off is limited to the brief period of energy transfer from the leg to the hip that occurs during the peak of APF power generation (the J3 hip joint power phase, Fig. 3). The energy transfer to the trunk (4.2 J) is relatively small, accounting for only 13% of the total work done by the APF during push-off. This transfer of energy to the trunk occurs at a time when trunk potential energy is reaching its minimum and kinetic energy is increasing. Thus, while the APF may contribute to maintaining the forward velocity of the trunk, it does not appear to significantly contribute to lifting of the trunk upward against gravity during the push-off phase of the stride cycle.

With only a limited direct effect of the plantar flexors on propulsion of the trunk, other mechanisms must be important. The pattern of hip joint power (Fig. 3) shows two additional phases of energy transfer (J5 and J1) from the leg into the trunk. Following push-off, the swing leg energy continues to increase slightly reaching its maximal energy level in early swing (Fig. 1). The further increase in leg energy occurs in early swing because of continued work by the hip flexors muscles as they assist in the forward acceleration of the leg. Beginning in mid swing phase, the swing leg begins to decelerate as potential and kinetic energy declines. The energy lost by the decelerating leg is partially absorbed by knee musculature, but the majority of the energy (18.6 J) is transferred across the hip joint to the trunk. This is nearly four and half times larger than the energy transfer to the trunk during push-off. Previous investigators (2, 3, 5, 11) have noted a similar transfer of energy from the swing leg to the trunk, though estimates of its magnitude relative to push-off energy transfer have varied from 1.6:1 to 3:1. The data from these previous studies and our data offer convincing support for the concept that the work done by the APF has only a very limited effect on the trunk during the push-off phase but is "stored" as potential and kinetic energy in the swing phase limb. This energy is subsequently recovered and ultimately transferred into the trunk as the swing leg is decelerated.

It has been hypothesized that the effect of the energy transfer to the trunk in terminal swing is the major mechanism of forward propulsion of the trunk during the stride cycle. This presumed effect is embodied in the term "pull-phase" used by Bresler & Frankel (2) to describe this portion of the stride cycle and lead Inman (11) to argue that a prosthetic limb which is too light may not be capable of returning enough energy to the trunk in terminal swing to supply adequate forward propulsion (11). However, despite the general agreement that a major transfer of energy to the trunk occurs during the later half of swing phase, the effect on propulsion of the trunk is less clear. During the period of energy transfer from the decelerating swing leg, trunk potential energy oscillates out of phase with trunk kinetic energy. This reciprocal change in trunk potential and kinetic energy allows for the inter-conversion of potential and kinetic energy within the trunk and is well recognized as an important mechanism for minimizing the energy cost of walking (21). The subjects in this study actually demonstrated a small net loss of total trunk energy because the decline in potential energy exceeded the corresponding increase in trunk kinetic energy. The reduction in total trunk energy of 3.3 J occurred in terminal swing phase despite the inflow of 18.6 J from the decelerating leg. There was variability in the magnitude of the trunk energy change between subjects, suggesting that differing degrees of trunk energy conservation occur among subjects as a result of individual differences in kinematic patterns. This variability may underlie the differences seen in previous studies that have shown conflicting patterns of terminal swing trunk energy ranging from a decline in trunk energy similar to that seen in this study (12, 29), essentially no change in energy (19) or a small increase in trunk energy (3). Regardless of the specific pattern of trunk motion, the magnitude trunk energy change is small relative to the large transfer of energy from the decelerating swing leg.

This mismatch between the energy transfer into the trunk and the small change in trunk energy level means that much of the energy from the decelerating leg must either be absorbed by eccentric muscle activity or transferred out of the trunk into the contralateral limb. Previous investigators (10, 12) have suggested that this "excess" energy is absorbed by the muscles of the contralateral leg as part of their control and restraint function during stance phase. Because this study did not perform simultaneous measurement of both lower limbs, verifying this energy flow was not possible. However, by assuming symmetry between the right and left legs, the pattern of hip joint power transfer of the contralateral limb can be simulated. From this analysis (Fig. 5), the period of swing deceleration and its corresponding transfer of energy into the trunk occurs at a time when energy is flowing from the trunk into the contralateral leg. Within the contralateral leg, some of this energy appears to be absorbed as a result of eccentric contraction of the ankle plantar flexors and hip flexor muscles (10, 12) as shown in Figs. 3 and 4. This study does not offer conclusive evidence but does suggest that much of the energy generated by the APF and hip flexors, initially used to accelerate the leg into swing, is ultimately absorbed by these same muscle groups in the contralateral leg as they control forward motion during stance phase. It is interesting to speculate that by using an eccentric contraction to absorb energy from the contralateral swing leg, the hip flexors and APF muscle

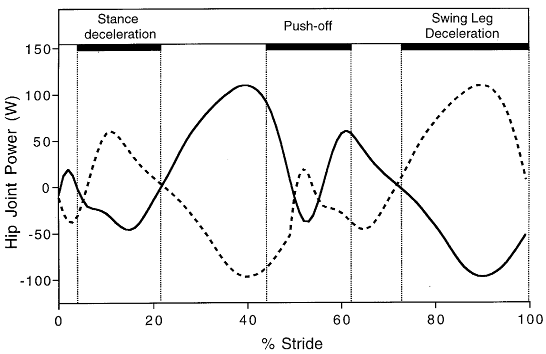

Fig. 5. Simulated bilateral hip joint power outputs showing the relationship between simultaneous energy transfers across both hip joints assuming right and left leg symmetry. Ipsilateral limb (—), simulated contralateral limb (- - -).

may be utilizing elastic storage of work during a stretch-shortening contraction to minimize the metabolic cost of the work needed to accelerate the leg later in stance.

Since it appears that the deceleration of the swing phase leg does not completely account for the energy needed by the trunk to ensure its forward progression, other sources of work are required. Possible mechanisms occur in early stance phase during the third phase of energy transfer from the leg to the hip, the J1 phase (Fig. 3). As the swing leg makes floor contact and stance begins, there is a brief period of impact absorption, followed by a period of energy transfer from the leg into the trunk during the J1 phase. A total of 6.3 J of energy are transferred to the trunk. Two potential sources of work exist that may account for this energy transfer. The first may be residual energy stored in the leg at the time of floor contact. As stance phase begins, total leg energy remains elevated above its midstance baseline level. Some of this energy is likely absorbed by the initial eccentric action of the knee extensors at heelstrike, but the presence of a phase of energy transfer across the hip into the trunk suggests the possibility that some of the remaining leg energy may contribute to the increasing trunk potential energy. Conceptually this may be considered as an extension of the "deceleration of the swing leg" which does not end with floor contact but lasts into the early part of stance phase. A second source of work has been shown by previous investigators (10, 26) to be the result of the midstance concentric contraction of the quadriceps contributing to the elevation of the trunk center of mass.

The findings of this study help to explain the gait abnormalities resulting from impaired APF function and further the understanding of the effects of orthotic and prosthetic interventions. From a clinical perspective, it is important to distinguish between the eccentric and concentric functions of the APF. The eccentric contraction of the APF during midstance, prior to push-off, performs two functions. First, it creates a moment (torque) about the ankle that resists dorsiflexon and, second, it absorbs energy. These actions help to control the forward movement of the trunk over the stance phase foot while preventing excessive dorsiflexion of the ankle. Common gait abnormalities associated with impaired APF function are reduced walking velocity and a shortened contralateral leg step length (15, 23, 25). Both appear to be important compensatory strategies. The magnitude of EMG activity, ankle movements and power generation of the APF are related to walking speed (17, 26). As walking speed is reduced, less ankle torque is needed to control the progression of the center of mass. Shortening the contralateral step limits the need to advance the trunk forward, thereby minimizing the destabilizing effects of allowing the center of pressure to move anterior to the ankle. Slower walking also reduces the acceleration of the contralateral swing leg resulting in a corresponding reduction in the need for the APF to absorb the energy transferred into the leg during contralateral swing deceleration. The use of an AFO that prevents dorsiflexion by mechanical stops or via a rigid ankle in prosthetic limbs effectively generates an ankle torque that can help to restore a more normal progression of the trunk over the stance phase foot (15) and allow for early heelrise.

The relative ease of substituting for the midstance action of the APF should be contrasted with the limited ability of orthotic and prosthetic devices to substitute for the forward acceleration of the leg during push-off. A source of work is required to accomplish this. The energy storing features of prosthetic feet (8, 22, 30) can supply 10–60% of the normal APF muscle work in push-off, though they function more effectively at faster walking speeds and during running. One compensatory adaptation used by amputees to substitute for lost push-off is increased concentric activity of the hip flexors during late stance and early swing to accelerate the leg forward via a pull off mechanism (4, 22, 30). Unfortunately, there is little objective data on the pattern of muscle power outputs in other populations with impaired APF function, but it is reasonable to assume that a similar compensatory strategy may be used when possible. Empirically, the importance of this can be inferred from brain injury populations in which central motor control abnormalities often prevent the development of new adaptive patterns of muscle use. In these patients, it is not uncommon for the limited ability to advance and accelerate the limb forward to be a major limiting factor in achieving functional ambulation.

Several limitations exist in this study. The timing and magnitude of APF activity varies considerable with walking speed and with a change from walking to running gait (17). This study specifically addressed the role of the APF at the self-selected walking speed and may not be applicable at other ambulation speeds. Only a single limb was studied and kinematic and kinetic symmetry was assumed. While there is evidence to support this (9), we cannot confirm that our subjects were symmetric. The somewhat asymmetric pattern of trunk energy changes during the first and second halves of the stride may suggest that some right–left asymmetry exists in our subjects. Only sagittal plane motion was analyzed; thus, effects of trunk rotation are unknown. Finally, the model used for the determination of muscle work assumes only singled jointed muscles. While this does not affect the overall findings of the study, the two-jointed nature of the gastrocnemius muscle can introduce uncertainty into the effect of activity of the APF on motion at adjacent joints, i.e. the knee. This was not specifically addressed in this study.

In conclusion, the most direct and immediate function of the work generated by the APF muscles during push-off is to increase the leg energy and to accelerate the leg into swing phase. The APF work is "stored" as kinetic and potential energy in the leg segment during the swing phase. This energy is ultimately transferred into the trunk during swing leg deceleration and contributes to maintaining the forward velocity of the trunk. There appears to be little direct effect of the APF on elevating the trunk center of mass against gravity. Other mechanisms, namely work during stance phase by other muscle groups, likely play an important role in this process.

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