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GAIT OF UNILATERAL BELOW-KNEE AMPUTEES

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The below-knee amputee has lost part of his locomotive system, not only the static supporting structure, but dynamic function of the foot-ankle complex as well. Lower-limb prostheses easily provide static structural supports, but not dynamic functions that correspond to muscle activities that have been lost. Consequently, good locomotion by the BK amputee requires adaptation in the joints of the remaining lower limb and, thus, compensation by the remaining musculature of the lower limbs.

Five active male unilateral BK amputees were used in a study of BK amputee gait (*1*). The subjects wore modular prostheses, with the supracondylar suspension variation of the PTB socket (*2*) and a SACH foot. Electrical switches were used on both shoes to measure foot position during stance phase. On the amputated side, knee motion was measured by an electrogoniometer. Muscle activity was recorded by use of an electromyograph and surface electrodes. The muscles investigated were the gluteus maximus, the quadriceps groups, and the hamstring group on the affected side; the gluteus maximus and vastus lateralis on the unaffected side.

Among the factors influencing the gait pattern of a unilateral BK amputee are the lost foot-ankle function and alteration of the normal knee-ankle mechanism, and the effect of the ground reaction upon the foot of the BK prosthesis.

As a result of the lost foot-ankle function, compensation in the amputee occurs at the knee joint on the amputated limb; in the foot-timing on the normal limb and in the muscle activity in both lower limbs.

TERMINOLOGY USED IN HUMAN LOCOMOTION STUDIES

A complete gait cycle (Fig. 1) is the period of time from which the heel of one foot contacts the ground to the next heel-contact of the same foot. Two distinct phases occur in this cycle: the stance phase and the swing phase.

Stance phase begins at the instant the heel of one foot contacts the ground and ends when contact with the ground is lost at toe-off of the same foot. Shortly after heel-contact, the sole of the foot makes contact with the floor. This event is referred to as foot-flat. The period between heel-contact and foot-flat is referred to as early stance. Following foot-flat is a period called mid-stance which occurs between foot-flat and when the heel loses floor contact at heel-off. During mid-stance the body weight advances directly over the supporting limb. Following heel-off, a period of forward body propulsion or push-off occurs prior to the foot leaving the ground at toe-off. This period between heel-off and toe-off is referred to as late stance phase.

The sequence of events in stance phase that have just been described will, in this article, be referred to as *foot-timing*.

Swing phase begins at toe-off and continues until the heel contacts the ground. Swing phase is divided into two equal periods, early and late. Three events occur in the swing phase: acceleration, mid-swing, and deceleration. Acceleration begins at toe-off and continues to mid-swing when the swinging leg passes directly beneath the body. Deceleration occurs after mid-swing until the heel of the forward moving limb makes contact with the ground.

During walking, alternation from stance phase to swing phase of each leg results in a period when both feet are in contact with the ground simultaneously. This period is known as double-support or double-stance.

THE EFFECTS OF LOST ANKLE FUNCTION ON NORMAL KNEE MOTION (Fig. 2)

In normal subjects the knee flexes 15 deg. (*4, 8, 11, 17*) to maintain the center of gravity of the body level as it moves (*15*). Because this amount

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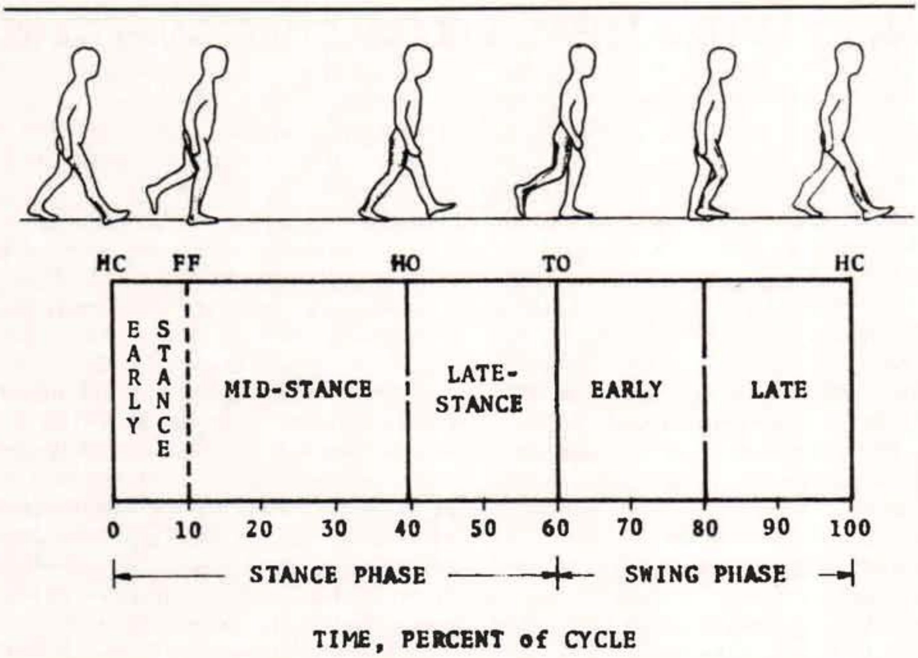

Fig. 1. Components of a gait cycle. HC - Heel-contact; HO - Heel-off; FF - Foot-flat; TO - Toe-off.

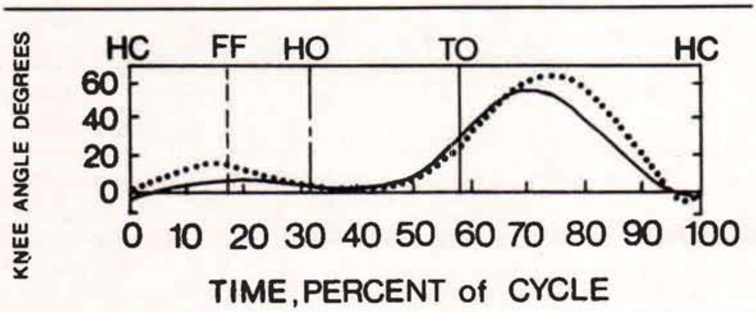

Fig. 2. Knee motion for the prosthetic side. Solid line (_____): Knee motion curve for amputee; Dotted line (. . .): Knee motion curve for normals.

of controlled plantar-flexion does not occur in the SACH foot, the amputee must compensate by reducing the amount of knee flexion on the affected side to approximately 7 deg. during stance (*3*). If the amount of knee flexion were not reduced, but the knee were flexed as much as a normal subject (approximately 17 deg.) a noticeable limp would occur during stance phase. The limp would result in the dissipation of more energy because the center of gravity is raised and lowered an excessive amount (*15*).

In late stance phase the ankle begins to plantarflex in the normal subject, and at toe-off has reached an angle of approximately 10 to 15 deg. (*4, 8, 11*) (Fig. 2). The lack of plantar-flexion in the SACH foot at this period of the gait cycle presumably accounts for a mean knee flexion of about 30 deg. occurring at toe-off on the amputated limb (*3*). This value is lower than that found in studies of normals who have shown average knee flexion values of 37 to 43 deg. at toe-off (*4, 8, 11, 17*).

The interaction of a normal knee and ankle during late stance phase assists in lowering the body's center of gravity smoothly with a vertical displacement of about 5 cm. (*7*). If the amputee's knee flexed at toe-off to the same extent as a normal subject, his center of gravity would descend more than the usual 5 cm. and result in a noticeable limp. The amputee's reduced knee flexion at toe-off compensates for his lost ankle plantar-flexion in late stance phase, and thus helps to prevent an exaggerated vertical excursion of his center of gravity.

During swing phase, peak knee flexion on the amputated side was approximately 57 deg. and occurred at 70 percent of the gait cycle (*3*) (Fig. 2). Studies of normal subjects have shown peak knee flexion of a normal knee in swing phase to occur between 70 and 75 percent of the cycle and vary between 61 and 68 deg. (*4, 8, 11, 17*). These studies also showed that the plantar-flexion attitude of the normal ankle, on the average, was from 7 to 10 deg. at the same instant when peak knee flexion occurred. A SACH foot does not attain a plantar-flexion attitude, as does a normal ankle, during knee flexion in swing phase. Thus a lesser degree of knee flexion is sufficient on the prosthetic side to keep the artificial foot clear of the ground during swing phase.

THE EFFECTS OF LOST ANKLE FUNCTION ON FOOT-TIMING (Fig. 3)

In the study (*3*), the foot-timing for the BK amputees was asymetrical. The stance phase on the affected side occupied 57 percent of the cycle and the swing phase 43 percent, while on the normal limb, stance phase lasted 63 percent and swing phase 37 percent. This disharmony in the duration of stance could be explained as being the result of an early toe-off by the amputated limb owing to loss of the push-off function of ankle plantar-flexion.

In normal subjects the gait pattern between the two limbs is symmetrical. Stance phase has been found to occupy 60 to 62 percent of the cycle and swing phase to occur between 38 and 40 percent (*3, 4, 6, 9*).

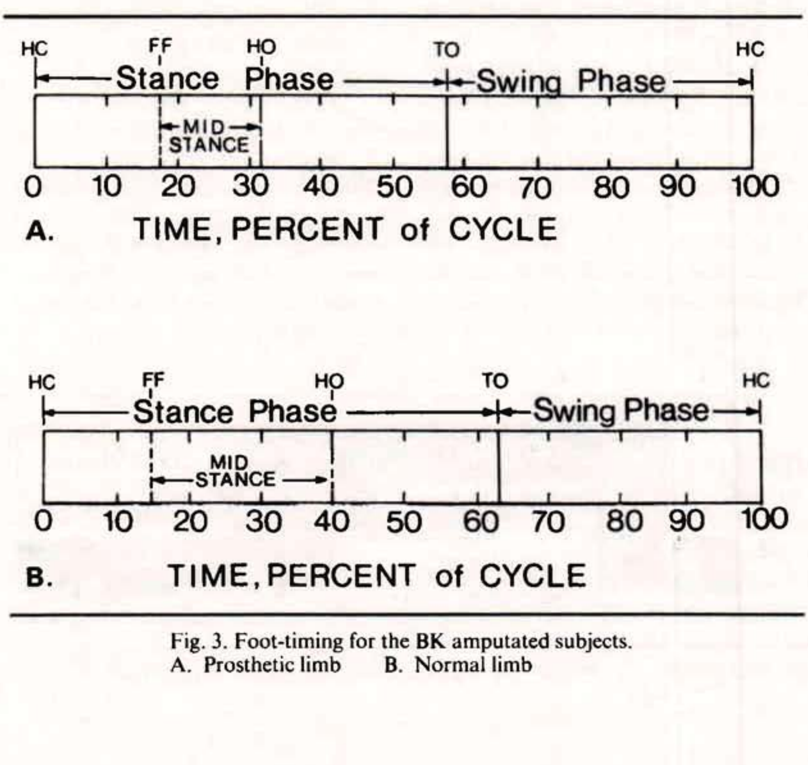

Fig. 3. Foot-timing for the BK amputated subjects.
A. Prosthetic limb B. Normal limb

In the BK amputee, foot-flat occurred on the affected side an average of 17 percent of the gait cycle, and in the contralateral limb an average of 15 percent (*3*). Foot-flat in normal subjects has been reported taking place at approximately 9 percent of a normal walking cycle (*3, 4*). Compression of the heel cusion of the SACH foot seems to be responsible for an elongation of the period between heel-contact and foot-flat in the amputated limb.

Lack of true ankle function in the prosthetic limb affected foot-timing of the normal limb (*3*). According to Elftman (*5*) and Inman (*7*) ankle plantar-flexion provides energy for forward motion of the body. This loss of energy from the prosthetic limb appears to result in a longer duration before foot-flat occurs on the normal limb, which probably assists in movement of the body over the foot. If foot-flat on the contralateral limb were to occur at approximately 9 percent of the gait cycle, as seen in normal subjects, additional muscular effort would be required to move the body forward over the foot, since little assistance can be expected from the prosthetic limb. It appears that postponing foot-flat on the contralateral side until a later period in stance phase (i.e. approximately 15 percent) allows the body to move forward, pivoting on the heel of the normal foot.

Absence of dorsi-flexion in the SACH foot affects the foot-timing on the amputated side resulting in early occurrence of heel-off (*3*). Heel-off occurred in the prosthetic limb at an average of 31 percent of the walking cycle (*3*), compared to 43 percent in normal subjects (*4*). In a normal subject, during midstance, the body moves forward over the foot resulting in approximately 8 to 12 deg. of dorsi-flexion of the ankle (*4, 8, 11*). Perry (*13*) stated that dorsi-flexion of approximately 10 deg. in mid-stance allows the body to move forward more easily over the foot. The earlier occurrence of heel-off in the gait cycle of the amputee would appear to be a result of the lost dorsi-flexion and permit the amputee to move his body forward over the artificial foot.

DOUBLE SUPPORT PHASE (Fig. 4)

Double support of the below-knee amputee subjects showed an average duration of approximately 20 percent made up of approximately 9 percent occurring at heel-contact of the amputated limb and toe-off of the normal limb and approximately 11 percent occuring when the foot positions were reversed. This increased time period of 2 percent (i.e. 11 to 9 percent) appears to be related to the shortening swing phase duration of the normal limb. Between heel-off of the prosthetic limb and heel-contact of the normal limb, the amputee pivots forward through space on the fore part of the artificial foot. Early heel-contact on the normal limb shortens this tenuous period on the prosthetic limb and increases (i.e. by 2 percent) the duration of double support occurring between heel-contact of the normal limb and toe-off of the amputated limb.

THE EFFECTS OF LOST ANKLE FUNCTION ON MUSCLE ACTIVITY

As the amputee walks, external forces (ground reaction) act upon the foot of the prosthesis. The artificial foot is thought of as a lever through which the ground reaction acts to produce moments occurring about the knee joint. Influenced by these moments, the amputee's musculature responds by attempting to balance the moments produced about the knee.

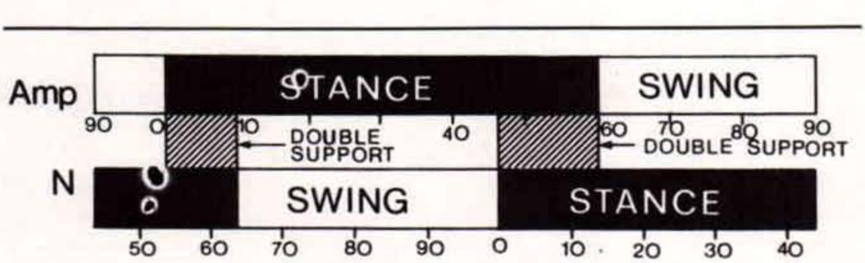

Fig. 4. Double support. Amp - amputated limb N - normal limb

The muscles in the affected limb investigated in the BK study (*3*) (i.e. gluteus maximus, quadriceps group, and hamstring group) were found to be active in early stance phase as has been reported by other investigators in studies with normal subjects (*1, 4, 5, 18*). However, the activity of muscles in the amputee subjects was found to be of longer duration than that found in normal subjects reported in the University of California Study (*18*).

A comparison of the myoelectric activity of the muscles investigated in the affected limb (*3*) and the activity found in the same muscles in the normal subjects in the University of California Study (*18*) referred to above are presented in Figure 5.

The activity recorded from gluteus maximus in the affected limb occurred from heel-contact to approximately 22 percent of the gait cycle (*3*) compared to heel-contact to 12 percent in normal subjects as reported in the University of California Study. Also, in the amputated limb, muscle activity was observed in the quadriceps group (i.e. rectus femoris, vastus medialis, and vastus lateralis) from heel-contact to approximately 27 percent of the cycle (*3*) compared to heel-contact to an average of 18 percent in the University of California Study. In the hamstring group (i.e. medial and lateral hamstrings) of the amputee subjects, muscle activity was present from heel-contact to approximately 25 percent of the cycle (*3*) in contrast to the University of California Study finding of heel-contact to an average of 8 percent of the gait cycle.

The increased durations of muscle activity in early and mid-stance phase found in the amputees (*3*) can be explained as being a compensation for lost ankle function. The calf muscles in normal subjects act from about 10 to 55 percent of the gait cycle (*18*) and are thought to have an important stabilizing effect upon the knee joint in mid-stance phase (*14, 16*). Sutherland (*16*) contends that the restraining action of the ankle plantar-flexors controlling dorsi-flexion in mid-stance allows the extrinsic forces (kinetic forces, gravity, and ground reaction) to extend the knee as the body moves forward over the fixed foot. Paul (*12*) mentions that from 10 to 25 percent of the gait cycle no muscle in the leg is suitably placed to resist flexion of the knee and hip simultaneously. It would appear that the indirect action of the ankle plantar-flexors plays an important role in stabilizing both joints in mid-stance. One

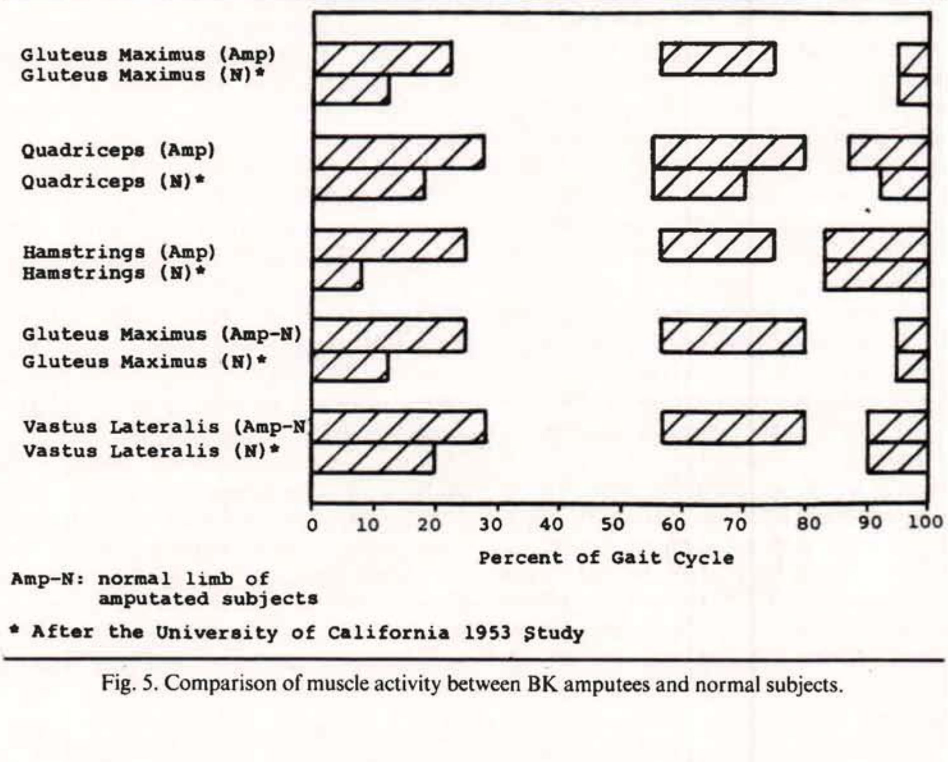

Fig. 5. Comparison of muscle activity between BK amputees and normal subjects.

could speculate that because an ankle plantar-flexion moment in normal subjects occurs from approximately 15 to 60 percent of the gait cycle (*16*) this moment causes a knee extension moment and, in turn, a hip extension moment. Because plantar-flexion action and, therefore, the plantar-flexion moment is lost in the below-knee amputee, the knee and hip would tend to flex in mid-stance if the amputee's muscle activity behaved as in a normal individual. Thus, hip and knee extensors showed a prolonged period of activity, presumably in order to counteract flexion moments at the knee and hip joints.

In the amputee subjects, muscle activity in the knee and hip extensors disappeared in late mid-stance. However, the ankle plantar-flexors in normal subjects cause a knee and hip extension moment. Because the amputated subjects have lost the ankle plantar-flexors, what prevents the knee from buckling during late mid-stance and early late-stance prior to the initiation of knee flexion in late stance? Sutherland (*16*) found in normal subjects that the body weightline falls in front of the knee and ankle joints at some point after 26 percent of the walking cycle. He used this finding to emphasize that gravity alone could not extend the knee as it would also tend to dorsi-flex the foot, which, in turn, would produce a flexion moment about the knee. He therefore hypothesized that the restraining action of the plantar-flexors on ankle dorsi-flexion contributes to knee stability. In the below-knee amputee the loss of ankle dorsi-flexion, making the artificial foot a somewhat rigid lever pivoting about the forefoot, reduces the need for plantar-flexion action in late mid-stance (i.e. 25 to 31 percent) to assist in stabilization of the knee. It is concluded that the effects of gravity acting in front of the knee joint at approximately 26 percent of the cycle (*16*) together with the effects of the ground reaction on the artificial foot act to stabilize the knee joint in late mid-stance and early late-stance phases without the requirements of plantar-flexion muscular activity which seems to be so necessary in normal limbs.

Plantar-flexion of a normal ankle in late-stance phase initiates hip and knee flexion to begin swing phase (*7*). In early swing phase in a normal subject, the swinging leg receives further energy from the hip flexors (*5, 7*). However, a below-knee amputee having lost the foot-ankle push-off mechanism requires increased action of the hip flexors to initiate swing phase. This results in an increased heel rise of the prosthetic limb during early swing phase. It is thought that the activity found in rectus femoris, vastus medialis, and vastus lateralis (*3*) served to control excessive heel rise on the affected side during early swing phase. By comparison, no activity has been reported in the same muscles during early swing phase in studies of normal subjects walking at a normal cadence (*1, 4, 18*). Rectus femoris in the amputated subjects (*3*) showed a longer duration of activity in early swing phase (between 55 to 80 percent of the cycle) as compared to 55 to 70 percent in the normal subject (*18*). This longer period of activity of rectus femoris is probably a result of a damping effect by quadriceps on the heelrise of the prosthesis to counteract the increased activity of the hip flexors as referred to above. Also, activity in rectus femoris may serve to accelerate the leg in swing phase after maximum knee flexion has occurred (i.e. at 70 percent of the cycle).

Myoelectric activity appeared in the gluteus maximus and the hamstrings of the affected limb during early swing phase (*3*). However, no activity has been seen in these muscles in gait studies using normal subjects. The activity in these muscles in the amputee is probably a counterbalance to excessive activity in the hip flexors and quadriceps muscles.

The electromyographic findings in gluteus maximus and vastus lateralis in the amputee's normal limb (*3*) differ from findings in the same two muscles reported in normal subjects studied elsewhere (*1, 4, 10, 18*). In stance phase, activity in gluteus maximus was present from heel-contact to 25 percent of the walking cycle (*3*) as compared to only 12 percent in the University of California study (*18*). Elftman (*5*) stated that an important source of energy in the initiation of forward swing of a limb came from push-off by the calf muscles. He postulated that additional energy is still required for forward swing is provided by the hip extensors of the supporting limb and the hip flexors of the swinging limb. The loss of push-off in the affected limb may account for the longer period of activity observed in gluteus maximus in the normal limb (i.e. supporting limb) while swing phase was occurring in the affected limb.

Vastus lateralis in the amputee's normal limb (*3*) was active in stance phase for an average of 8 percent of the cycle longer compared to normal subjects investigated elsewhere (*18*). This somewhat longer duration of muscle activity may be due to an increased energy requirement for forward motion as a compensation for lost energy input on the amputated limb.

In early swing phase, both gluteus maximus and vastus lateralis in the amputee's normal limb were active (*3*), a condition which has not been reported in normal gait studies. It is quite feasible that a more than normal amount of push-off occurs in late stance phase on the normal limb in order to provide additional impetus to assist forward motion of the body during early stance phase on the prosthetic limb. As push-off initiates hip and knee flexion to begin swing phase (*7*), the activity seen in gluteus maximus and vastus lateralis could serve to counterbalance the increased flexion moments in both the hip and knee joints produced by the increased intensity of push-off.

SUMMARY

Compensations occur in the gait pattern of the below-knee amputee due to loss of the normal foot-ankle mechanism. The compensations are seen at the knee joint of the affected limb, in the foot-timing on the normal limb, and in the activity of the lower-limb muscles studied in both the affected and contralateral limbs. The loss of a normal foot and ankle results in the alteration of the normal walking pattern as follows:

1. A longer stance phase occurred consistently in the normal limb and a shorter stance phase duration in the amputated limb. Also, the foot-timing during stance phase of the two limbs varied the one from the other.

2. Knee motion in the amputated limb followed the same general pattern as seen in normal knee motion. However, the magnitude of knee flexion in the amputated limb was reduced in stance phase, at toe-off, and at peak knee flexion during swing phase.

3. The phasic myoelectric activity of the muscles studied in both the amputated and non-amputated limbs increased in duration as compared with the same muscles investigated elsewhere in normal (i.e. non-amputated) subjects.

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