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Benchmark data for elderly, vascular trans-tibial amputees after rehabilitation

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Abstract

Benchmark data for lower limb amputees is often limited to young subjects who have had their amputations as the result of trauma. The majority of trans-tibial amputees rehabilitated are, however, elderly vascular amputees who may have different gait characteristics than their younger counterparts. Without biomechanical analyses to provide such benchmark data for this group it is not possible to compare the effects of different rehabilitation programmes, gait training regimens, or prosthetic devices.

Twenty elderly vascular trans-tibial amputees rehabilitated at The Queen Elizabeth Centre, Ballarat, Australia and at least six months post-amputation were measured in respect of kinetic and kinematic parameters, and relationships between gait speed, consistency, and function were demonstrated. Further, an unexplained vertical ground reaction force pattern was demonstrated in faster, more functional amputees.

Introduction

While different rehabilitation programmes and types of prostheses exist for lower limb amputees, no benchmark biomechanical analyses are available for elderly trans-tibial vascular amputees against which the performance of patients leaving a rehabilitation programme can be measured.

Such profiles exist for fit people of all age groups, and in part for those with pathology (Cheung *et al.*, 1983; Olney *et al.*, 1979). Without detailed gait profiles for fit, elderly, vascular amputees there is no standard against which to assess the relative differences between the various rehabilitation approaches for this group.

This study, conducted at The Queen Elizabeth Centre, Ballarat (QECB), quantifies the gait performance of vascular trans-tibial amputees who have participated in a gait training regimen which is particularly designed to facilitate early discharge from in-patient treatment. The training regimen relies on the whole method of motor re-education, minimising the use of support rails, rather than the more traditional progressive part methods and early reliance on rails. The philosophy of early discharge is balanced against the necessity of ensuring a gait pattern which is economical of effort and promotes optimal functional mobility.

The relatively short in-patient stay at the QECB for new amputees, 17 days on average in 1991/92 (Carter, 1992) compared to much longer stays in other settings (Baker and Hewison, 1990), permits this group of clients to return home quickly after surgery and to expect a high level of gait quality.

It is envisaged that clinicians who advocate the use of different therapeutic regimens and prostheses will be able to assess the length of stay and gait performance of their clients in the light of the parameters investigated in this study.

Rehabilitation outcomes can be measured in several ways, dependent upon the perceived goals of care. Length of time spent in hospital provides an estimate of treatment cost, while functional measures provide information about the ability of individual clients to live independently once the rehabilitation process has been completed.

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More detailed and objective measures are required, however, when considering the efficiency and effectiveness of particular treatment techniques offered by individual therapies, such as the gait re-education programmes offered by physiotherapists to trans-tibial amputees.

While some base-line measures of amputee gait through objective gait analysis have been reported, there is currently no basis for choosing a particular programme, and no ongoing evaluation of outcomes except in terms of length of hospital stay, which gives no indication of the quality of walking or function for those discharged.

Method

Twenty vascular trans-tibial amputees rehabilitated at the QECB at least 6 months previously were analysed using a Selspot Movement Monitoring System and AMTI force plate. All subjects walked without walking aids for the test, although three required a cane for outdoor ambulation.

All subjects wore their usual prosthesis, patellar-tendon-bearing prostheses made using titanium componentry and SACH feet. Prior to data collection all subjects were reviewed by a qualified prosthetist to ensure appropriate fit and alignment of the prosthesis worn.

Six light emitting diodes (LEDs) were placed on the subjects prior to sagittal plane data collection. Markers were placed at the tip of the acromion, the greater trochanter of the hip, the mid-point of the prosthesis at the patellar bar, the mid-line at the foot attachment to the shank, at the heel and at the point of what would be the fifth metatarsal head. The subsequent identification of the limb and body segments was used in the calculation of joint forces, moments and powers in the manner of Winter (1979), and the resulting data normalised by dividing by body weight.

Results and discussion

Parameters selected for further analysis were:

- preferred walking speed;
- functional scores;
- temporal and spatial parameters;
- kinetics, including:
  - vertical ground reaction force (GRF);
  - joint moments of force and power patterns;
  - hip and knee interaction

Preferred walking speed

The mean preferred walking speed of subjects tested was 0.8 $m.s.^{-1}$, with a standard deviation (SD) of 0.19 $m.s.^{-1}$ Skinner end Effeney (1985) reported a mean walking speed of 0.75 $m.s.^{-1}$, SD = 0.15 $m.s.^{-1}$, and, as these data are the compilation from the literature for vascular amputees, it is probably indicative of the typical performance of rehabilitated amputees.

Functional scores

To ensure that subjects were performing at a functional level which was similar to those with whom comparisons were being made, functional scores were ascertained for each subject.

The functional measure, reported by Day (1981), was designed specifically for the amputee population and takes into account the necessity for donning and doffing the prosthesis as well as its use in indoor and outdoor activity. The scores obtained on the Day scale display a reasonable spread over the population group (Fig. 1), and preferred walking speed was found to correlate highly with this functional ability measure ($r = 0.63$, $p = 0.0018$).

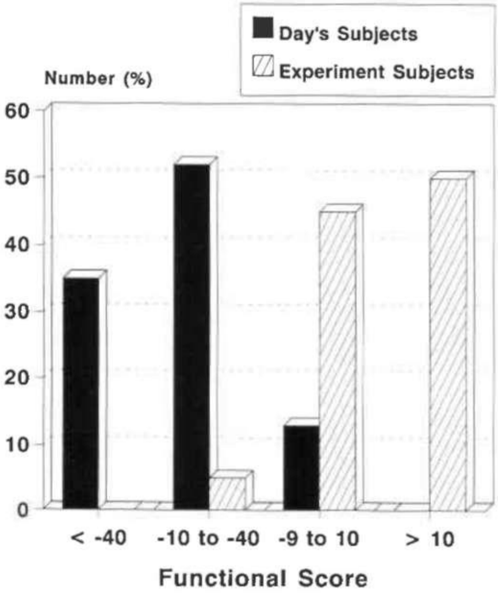

Fig. 1. Day scores for Day's subjects and all experimental subjects.

Temporal and spatial parameters

The group of vascular amputees described in the current study had a mean stride time of 1.3 s (*SD* = 0.14 s) and a mean stride length of 0.97 m. A statistically significant association was demonstrated between prosthetic stride time and speed ($r = -0.77$, $p = 0.0001$), and between prosthetic stride time and the Day functional score ($r = -0.65$, $p = 0.0025$).

These data support the argument presented by Dewar and Judge (1980) who contended that stride time may be used as a substitute measure for walking speed, even for those with pathological gait patterns. Cheung *et al.* (1983) verified this association when monitoring the performance of a group of amputees as they progressed through rehabilitation.

Symmetry

Of the elderly vascular amputees studied, 63% of subjects had a longer prosthetic than non-prosthetic step, and 37% had a longer duration prosthetic step than non-prosthetic. Symmetry calculations were made by division of the shorter step into the longer one, no matter which was the prosthetic step, providing a non-directional measure of symmetry. Using this method, step length symmetry and preferred walking speed were associated positively and significantly ($r = 0.56$, $p = 0.014$).

A significant association was also found between prosthetic step length and walking speed ($r = 0.65$, $p = 0.0026$) in the experimental group, and between prosthetic step length and step length symmetry ($r = 0.68$, $p = 0.0012$), indicating that those amputees taking longer prosthetic steps were tending to a more even spatial gait pattern, as well as walking faster.

Step timing symmetry, however, displayed no significant relationship to either step length symmetry ($r = 0.11$, $p = 0.64$) or walking speed ($r = -0.33$, $p = 0.17$), Indeed, the tenuous link between temporal symmetry and speed is negative, so that the lower the ratio (where 1 is the best symmetry score possible), the higher the walking speed.

These data support the contention of Winter and Sienko (1988) that pursuit of absolute gait symmetry may be unrealistic and unattainable for trans-tibial amputees, casting doubt on the wisdom of equating perfect symmetry with optimal amputee gait performance.

While it is possible to maintain spatial symmetry with the prosthesis, unless step timing is compromised, walking speed (and by inference, functional ability) will be reduced.

Kinetics

Vertical ground reaction forces (GRF)

Three basic patterns in the vertical GRF were identified (Fig. 2). These were the two peak pattern (seen in subject 20), typically recorded in the normal gait pattern (Andriacchi *et al.*, 1977), a three peak pattern not typically

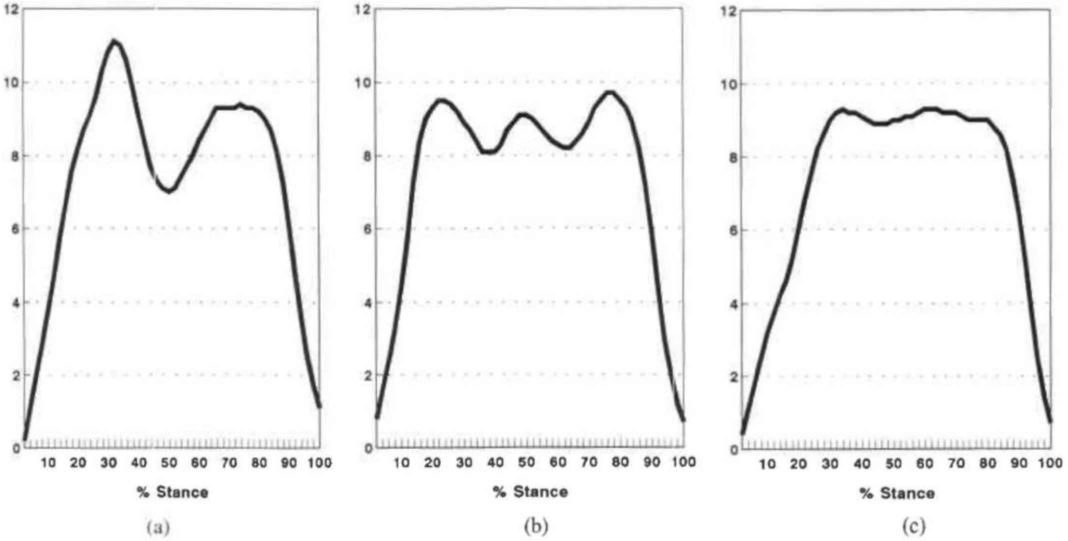

Fig. 2. Three sample patterns of vertical ground reaction force.
a) two peak pattern b) three peak pattern c) flattened pattern.

described (Subject 2), and a flattened pattern (Subject 5) where Z_1, Z_2, and Z_3, show little difference in magnitude.

Because the three vertical GRF pattern types are nominal data only, an association between the types and preferred walking speed was investigated using the contingency coefficient (Siegel, 1956). Analysis revealed a significant relationship ($C = 0.61$, $p = 0.027$) between the pattern type and the preferred walking speed for this group of vascular trans-tibial amputees, with those walking at fast speed most likely to have a three peak vertical ground reaction force pattern, and those walking slowly to have a flattened pattern.

This unexpected relationship may have been due to the nature of walking style adopted by faster walking amputees to maintain that speed. In normal walking the foot does not become a rigid lever for the plantarflexors until the toes have reached full extension, just prior to push off. For the amputee, however, once the SACH heel has compressed and decompressed, the rigid wooden keel provides leverage if a preliminary mid-stance push is needed.

Alternatively, the faster amputees may have compressed the SACH heel to such an extent that the wooden keel was struck prior to decompression, creating a vertical force which subsided once body weight was transferred to the front of the foot and decompression begun. No other authors have identified such a relationship, and more work needs to be done in this area to determine the relevance and implications of the association identified.

Seliktar and Mizrahi (1986), analysing the force patterns for 23 trans-tibial amputees, pointed out that even in normal gait the shoes worn have an effect which is complex and individual to both the shoe type and the heel itself. This variation in shoe type, which was not controlled in this study, may help to explain the larger inter-subject variability (CV = 0.17) observed here and also reported by Winter (1984) for normals. Intra-subject variation for this parameter was relatively low (mean CV = 0.08 $N.kg^{-1}$, SD = 0.03 $N.kg^{-1}$), again consistent with Winter's findings (1984).

The moment patterns at the ankle, hip, and knee for the subjects measured in this study had higher intra-subject mean variations (mean CV = 0.16 $Nm.kg^{-1}$, SD = 0.09 $Nm.kg^{-1}$, mean CV = 0.54 $Nm.kg^{-1}$, SD = 0.26 $Nm.kg^{-1}$, and mean CV = 0.36 $Nm.kg^{-1}$, SD = 0.17 $Nm.kg^{-1}$ respectively) than that of the vertical GRF. Addressing the same phenemenon in normal subjects, Winter (1984) surmised that the individual joint motor patterns provide a measure of the flexibility of the motor system to produce the same over-all response patterns.

Preferred walking speed was found to correlate negatively ($r = -0.46$, $p = 0.046$) with the relative time taken (T_1%) to attain peak vertical GRF (Fig. 3). This implied that subjects who walked at the highest speed loaded their prosthetic limbs most quickly (as a proportion of their total stance period) as might be expected, and this provided the basis for selecting the best walking performance for each subject over their recorded trials. This "best performance" trial for each subject was then used for analysis of inter-subject performance, and for averaging, although all trials were used calculations of intra-subject variation.

Individual joint moments, and power patterns

Ankle

The mean ankle moment throughout the

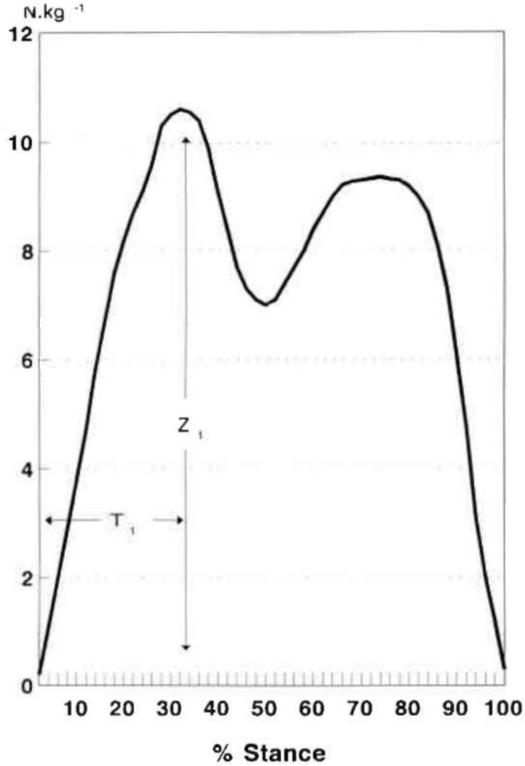

Fig. 3. The time taken (T_1) to reach Z_1, the peak vertical GRF.

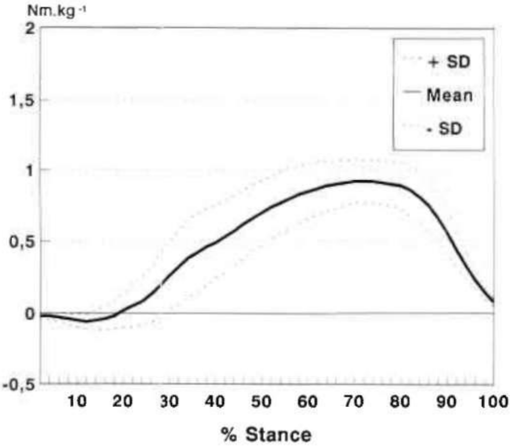

Fig. 4. Ankle moment pattern for the duration of stance phase (all subjects).

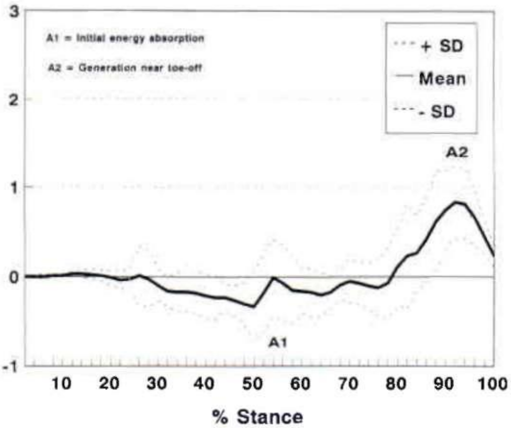

Fig. 6. Mean ankle power pattern for all subjects.

stance phase for the "best" trial of the available 19 experimental subjects appears in Figure 4.

The general pattern of ankle moments for trans-tibial amputees was consistent with that reported by Winter and Sienko (1988) who reported a preliminary dorsiflexor moment followed by a gradually increasing plantarflexor moment peaking in late stance (Fig. 5). In the group of older amputees in the current study, however, the initial moment continued as dorsiflexor for an average of 20% stance. Winter and Sienko (1988) described the duration of dorsiflexion as 18% of stride, where stance for their group was said to be 60% of the total stride. Thus for Winter and Sienko's group of 5 amputees the dorsiflexor moment lasted a mean of 30% of stance, slightly longer than for this experimental group, while for normals it is cited as lasting only 3% of stride (Winter and Sienko, 1988).

Winter hypothesised that the rigid ankle

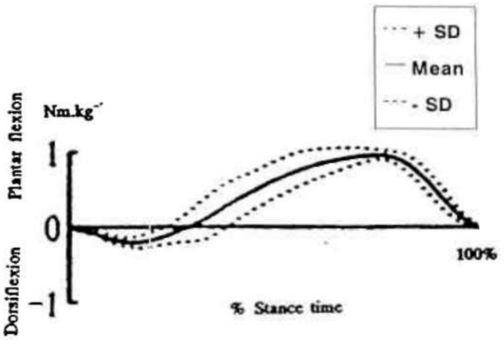

Fig. 5. Ankle moment patterns for five trans-tibial amputees (adapted from Winter and Sienko, 1988).

generates an "internal dorsiflexor moment" (Winter and Sienko, 1988) from heel strike to foot flat, compounded by a marked delay in the rotation of the amputee's shank forward over the prosthetic foot. This is consistent with the findings of Zernicke *et al.* (1985) who noted that the centre of pressure in the SACH foot remained at the posterior section of the foot for 43% of stance while for normals this is only so for 34% of stance.

The power patterns at the ankle for all subjects (Fig. 6) showed a typical pattern of energy absorption (A1) until late stance, when energy is then generated (A2).

These data, however, differ from those reported by Winter and Sienko (1988) for the latter part of the stance phase (Fig. 7). They reported initial energy absorption (A1) as the prosthetic foot deformed in dorsiflexion from heel-strike to mid-stance. This energy is not returned, according to Winter, with no comparable A2 power burst at terminal stance for trans-tibial amputees using SACH feet.

Data recorded for the 19 vascular amputees tested in this study showed an obvious A2 power burst of around one third of the normal magnitude (mean=1.1 $W.kg^{-1}$, SD=0.5 $W.kg^{-1}$). While this disparity may have been due to some notional difference in resilience of Australian SACH feet, or to the altered pattern of the amputees' gait trained at the QECB, it is more likely due to the difference in the definition of the foot segment for calculation of the ankle angle.

Since power is calculated as the product of angular velocity and joint moment, the ankle

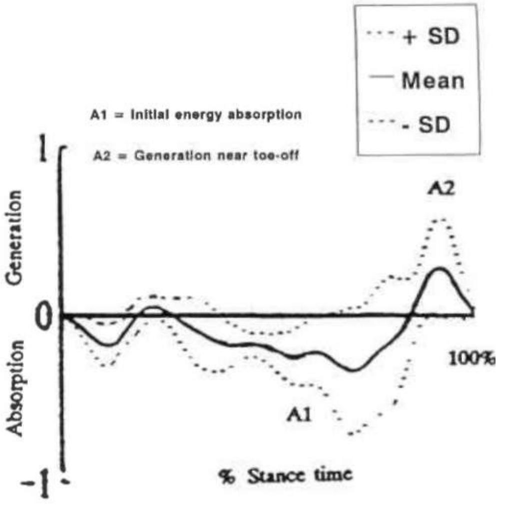

Fig. 7. Ankle power patterns for five trans-tibial amputees (adapted from Winter and Sienko, 1988).

powers recorded in the present study may be considered as a measure of the absorption and subsequent return of energy within the prosthetic foot.

Although Winter (1984) identified ankle power as the key to variation in a normal individual's walking speed, in the experimental group peak ankle power did not correlate significantly with preferred walking speed ($r = 0.37$, $p = 0.12$). Rather it was the peak hip power, occurring in the second half of the stance phase, which was found to be significantly related to speed ($r = 0.069$, $p = 0.0011$), indicating that once the mechanical rebound of the SACH foot has been exhausted

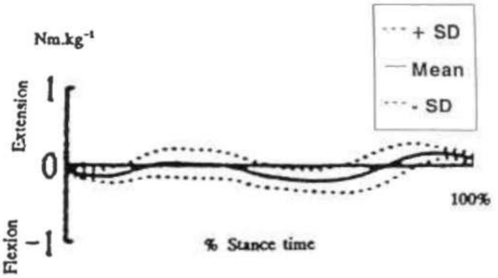

Fig. 9. Knee moment patterns for five trans-tibial amputees (adapted from Winter and Sienko, 1988).

as a source of propulsion, the vascular trans-tibial amputees in the present group utilised the musculature around the hip to optimise their functional walking ability.

Knee

Knee moments reported in this group (Fig. 8) are similar in pattern and magnitude to those reported for trans-tibial amputees by Winter and Sienko (1988) in Figure 9.

This pattern is similar to that reported by Winter and Sienko (1988) for five trans-tibial amputees (Fig. 11).

The average K3 fell within the normal limits for older subjects (Winter *et al.,* 1990), indicating that there remained a limiting action of the quadriceps on the shank in terminal stance. The level of variability in knee power was found to be significantly related to the preferred walking speed ($r = -0.68$, $p = 0.01$), indicating that consistency in power patterns at that joint is related to a better gait performance.

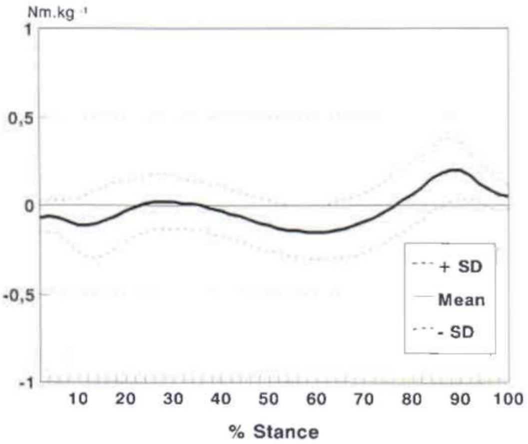

Fig. 8. Mean knee moment pattern for all subjects.

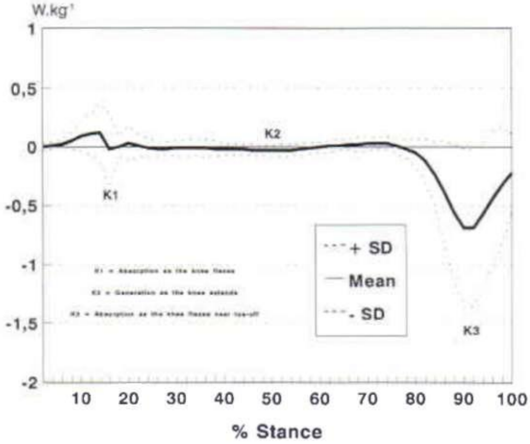

Fig. 10. Mean knee power pattern for all subjects.

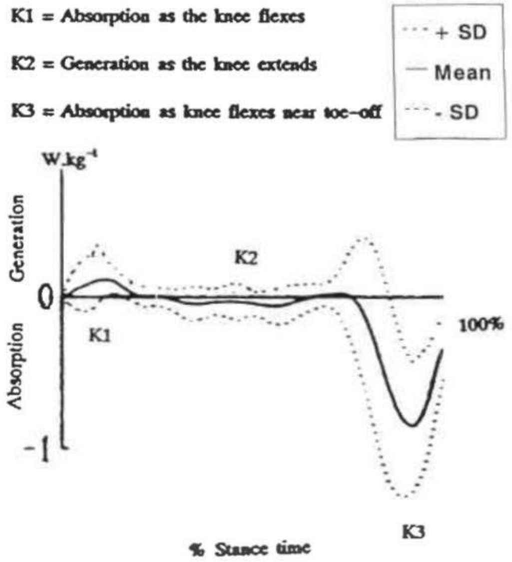

Fig. 11. Knee power patterns for five trans-tibial amputees (adapted from Winter and Sienko, 1988).

Hip

The general pattern of hip moments for trans-tibial subjects (Fig. 12) in the present study and those reported by Winter and Sienko (1988) in Figure 13 are similar in magnitude and direction. Extensor moments dominated the first half of the stance phase, followed by similar magnitude flexor moments.

Winter and Sienko (1988) reported that the mean variability of hip moments of force was greater in the population of trans-tibial amputees tested in that study than for normal subjects. In the present study, the degree of

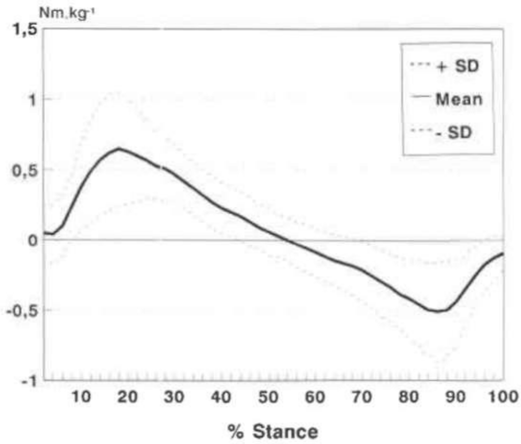

Fig. 12. Mean hip moment pattern for all subjects.

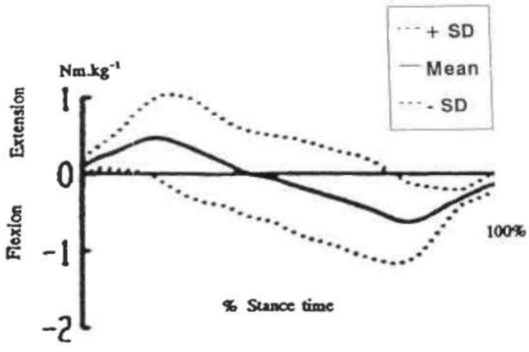

Fig. 13. Hip moment patterns for five trans-tibial amputees (adapted from Winter and Sienko, 1988).

variability in hip moments for amputees tested was found to correlate significantly with the preferred walking speed ($r = -0.72$, $p = 0.0052$), indicating that the higher the speed of walking performance recorded, the more consistent the hip response. This indicates that the trans-tibial amputees with the highest quality gait approached hip moment variability levels closer to the normal population.

This relationship between joint moment of force and preferred walking speed was not found for either the ankle moment variability ($r = 0.23$, $p = 0.44$), or the knee moment variability ($r = 0.028$, $p = 0.93$). Thus, in this population of trans-tibial amputees, the speed of walking is related to greater consistency only at the hip.

As previously stated the peak hip powers were found to be significantly associated with preferred walking speed. Like knee powers, more consistent hip power responses were found to be associated with higher preferred walking speeds ($r = -0.68$, $p = 0.01$), indicating that the well practised and experienced walkers used a consistent hip/knee power response on the prosthetic side to produce functional walking speeds.

Hip and knee interaction

Winter *et al.* (1990) described several ways of quantifying the interaction which can be demonstrated between the hip and knee during gait, particularly during the stance phase. For this group, covariance between the hip and knee moments for the "best" walk was calculated, where the linear association between them was identified.

For this calculation, the magnitude and

direction of the variation of the moments at each joint from their mean was tested. If both variables fall above or below their means at the same time, covariance will be positive, while if one variable is typically above its mean while the other is below, the covariance will be negative (STSC, 1989).

A negative covariance of moments at the hip and knee occurred in 69% of the current amputee group, the more negative the covariance recorded, the greater the preferred walking speed ($r = -0.47$, $p = 0.043$). A similar, though stronger, association was found between the Day functional measure score and the covariance of hip and knee moments ($r = -0.55$, $p = 0.016$), and the time (T_1) to reach peak vertical GRF ($r = 0.67$, $p = 0.0016$). The inference which may be drawn from these significant relationships is that the interplay between hip and knee demonstrated in normal elderly subjects (Winter *et al.,* 1990) also exists in trans-tibial amputees, and that the more complementary the interplay, the faster and more functional the amputee.

Conclusion

In conclusion, a general gait profile of elderly, vascular, trans-tibial amputees may be constructed. There was, within this group of 20 subjects, a marked variation in the traditionally consistent gait measures, with complex profiles of gait quality built around consistency in a few key parameters. While average walking speeds, functional measures, and other derived data were shown to match those reported in the literature, actual performance ranged from speeds of 0.4 $m.s^{-1}$ to 1.1 $m.s^{-1}$.

At the lower end of the scale were those vascular amputees with a low preferred walking speed and a low functional score. These subjects were slow to transfer weight to the prosthetic limb, strides were short and took longer than those of more active counterparts to perform. Step lengths were uneven, and knee and hip powers varied markedly from step to step. Peak hip powers were relatively low, probably because there were no consistent responses to the hip moments of force.

In contrast, more able amputees took long, quick strides. They quickly moved their weight onto the prosthesis and walked with evenly spaced, though unevenly timed steps. Hip moments of force were uniform for each step, providing a dependable base upon which to generate consistent hip powers, and knee power response was also steady from step to step. Relatively large magnitude peak hip powers on the prosthetic side produced the required walking speeds to carry out a more functional lifestyle.

It should now be possible to use these data to compare with that of rehabilitated amputees in other programmes with different philosophies, to ensure that they are chosen on merit, rather than on fashion.

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