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Biomechanical analysis of a novel automatically self-aligning ankle-foot prosthesis

Successful rehabilitation of amputees requires achieving optimal geometrical foot alignment in order to provide, efficient and comfortable locomotion over level ground. This optimal alignment is lost as soon as the amputee walks over inclines or changes shoes with a different heel height. This can cause discomfort and dissatisfaction with the prosthesis due to greater loading pressures at the socket interface and additionally cause unnatural gait deviations to compensate in order to walk on ramps and stairs.

A novel prototype self-aligning ankle-foot prosthesis has been developed with viscoelastic damping properties. This allows the prosthesis to adapt to anterior-posterior (AP) tilt alignments automatically over a limited range on a step-to-step basis thereby providing a dynamic alignment capability for changing requirements such as standing and walking on inclines and stairs. The hypothesis that the viscoelastic properties of the foot would dissipate excessive reaction forces facilitating improved proprioception such that the forces felt through the socket are a closer representation of those that actually control locomotion proved correct following trials with over 15 amputees. In this paper for the first time we report the results of these trials that have been carried out in order to both qualitatively and quantitatively study the biomechanics of the new generation of self-aligning prosthesis over varied walking surfaces. A six-axis pylon transducer and ground reaction force data was used to examine the dynamic loading characteristics of the prosthesis. The results showed significant reductions in plantarflexion bending moments at the distal interface of the socket and dramatic improvements in the levels of comfort and stability reported by amputees. The findings also indicated that amputees were more likely to increase loading on the prosthesis in a more normal way. We believe that this may diminish the risk of degenerative joint disease and other long-term complications related to asymmetrical loading between amputated and sound limb.

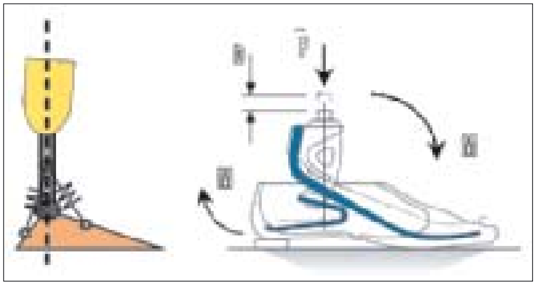

Fig. 1 An example of conventional ankle-foot designs. Ankle motion and resilience is generated predominantly through the loading of elastic design elements. The moments and forces generated are typically linearly proportional to the degree of deformation.

Introduction and Development

The aim of prosthetic foot alignment is to position the prosthesis relative to the body such that when the limb is loaded the forces and moments transmitted through to the stump interface are comfortable and provide optimum biomechanical function. However at present the true nature of alignment optimization remains unclear. In a study of 283 lower limb alignments from 20 amputees conducted by Zahedi et al. [11] it was found that there can exist considerable variability in what is considered a clinically satisfactory alignment. The results also showed that prosthetists could not readily repeat the exact alignment on the same amputees during different test sessions. The variability of satisfactory alignments may be partly explained by the adaptive capability of the body to self-adjust to optimize different alignments. However in a related study [12] by the same research group it was shown through biomechanical analysis that from a group of satisfactory alignments some alignments could be considered superior to others. In a more recent study by Blumentritt [1] investigated the effect of AP foot tilt alignment using 5 transtibial amputee subjects. The aim of their study was to determine the most efficient standing alignment which also minimises the stress on the residual knee structure. The distance between knee centre and load line was quantified using the LASAR posture device. They concluded from EMG measurements that a biomechanical optimum load line position of approximately 13 mm anterior relative to the knee centre is unlikely to over stress the knee ligaments and posterior knee capsule and will allow efficient standing and balance. The finding supports the anatomical alignment of the lower limb described in earlier work [9].

Humans as bipeds have an extraordinary ability to balance when

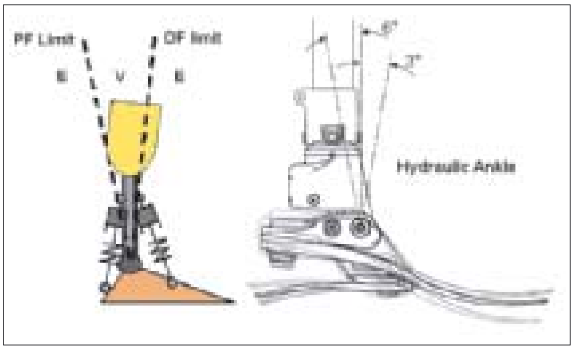

Fig. 2 Dynamic and physical model of the self-aligning prostheses shown by left and right images respectively. V = viscoelastic range of motion, E = elastic range of motion.

standing and walking on varied surfaces. This feature appears even more remarkable when considering that approximately two thirds of body mass is located two thirds of the body height above the ground and balances like an inverted pendulum. Lower limb amputees have a diminished capability to balance brought by the abnormal characteristics of a prosthesis interfacing with the ground. For example amputees will no longer be able to control balance through an active ankle control strategy.

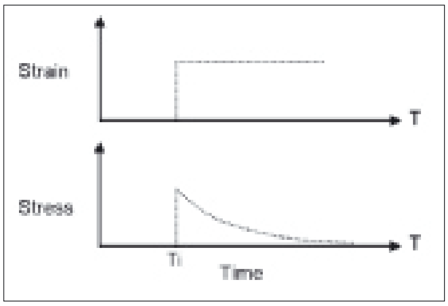

Fig. 4 Illustrative example of the stress-strain response produced by the Maxwell model viscoelasticity implemented in the Echelon foot design. When subjected to a stepwise strain input (Ti) reaction stress gradually dissipates over time. This unique mechanical characteristic gives the Echelon foot a time dependent adaptive quality which means abnormal stump interface loading is removed automatically shortly after limb loading.

It is obvious that outdoor walking surfaces are considerably more variable than the original alignment setup conditions found in a clinic. Prosthesis mal-alignment of even a few degrees caused by a simple change of shoe heel height and/or surface inclination will considerably alter the way the limb is loaded and thus optimization of alignment will be lost. The introduction of prostheses components with a user adjustable alignment facility allowing the amputee to re-adjust the AP tilt alignment following a change in shoe heel height has shown that this loss of optimization is readily apparent to amputees from stump interface loading [13]. Aside from the socket which acts as the other interface medium between human and prosthesis, the design and alignment of the prostheses can play a major role in functional balance in amputee standing and walking.

The mechanical characteristics of many current prostheses follow the same basic principle of creating ankle resilience from an elastic ankle-foot mechanism designed to deform under loading thus providing a combined means of ankle-foot resilience to motion and articulation. The moments and forces generated due to deformation generally follow Hooke's law for an elastic mechanism and the ankle-foot system will have an inherent equilibrium point when the foot is unloaded. This conventional design approach is illustrated in figure 1. Such feet also have no time dependent adaptive optimizing properties. Hence once the foot is loaded in a non-optimal way there exists no means to return to the optimum alignment condition shortly afterwards.

The need to develop means to adequately manage the additional forces generated which act to destabilise standing and walking when the limb is loaded under mal-aligned conditions suggest that true mechanical energy absorption rather than energy storage may play a key role in adaptive ankle behaviour. This idea is further supported when considering the known non-linear viscoelastic nature of muscle force generation [3, 5]. The mechanical stress-strain relationship of biological muscle suggests that a viscoelastic ankle mechanism may offer a better means of creating more adaptable ankle-foot prosthesis capable of adapting automatically to alignment perturbations [6].

Biomimetic Design

The aim of Biomimetic design is to enable the process of "natural optimisation" to occur through reduction of unnecessary effort required by the compensatory mechanism. The aim is to enabling amputee to more easily meet the requirements of any situation Activities of Daily Living (ADL) that they find themselves. For example, in order to stand straight on a slope and reduce compensating corrective action, a self aligning ankle joint, would enable an amputee to maintain correct posture, and minimises the muscular activity required to compensate for any inbalances. With this goal in mind a new type of ankle-foot prosthesis has been developed that comprises of independent unidirectional plantar and dorsiflexion fluid dampers combined with heel and toe spring elements. The foot does not have a fixed AP tilt alignment as per conventional practice, instead the foot is allowed to dynamically re-align (tilt) itself automatically on every step according to changing walking requirements and underfoot terrain on every step. A dynamic model of the ankle-foot design and its practical implementation called the Echelon Foot is shown in figures 2 and 3.

$$v_{in} + \frac{\dot{F}}{k} + \frac{F}{c} = \dot{u}$$

$$\frac{1}{k}\dot{F} + \frac{1}{c}F + \frac{1}{m}\int_0^t F d\tau = -v_{in} - v_o$$

The arrangement is designed such that the ankle acts viscoelastically during the initial phases of stance (region V) and elastically during the latter stages of stance (region E). The available effective viscoelastic range of motion during stance is controlled by the geometry of the actuators and can be altered either by controlled damping (e. g. by hydraulic lock) or by altering the AP tilt alignment of the socket or pylon. The hydraulic range of motion is typically biased to provide approximately 6 degrees of plantarflexion and 3 degrees of dorsiflexion respectively.

Fig. 3 The Echelon ankle-foot, practical implementation of the self aligning foot, with visco-elastic properties which can be adjusted via a valve system to suit an amputees preferred gait style.

Since the actuator operation is designed to be unidirectional and independent for plantarflexion and dorsiflexion, the stress-strain and damping characteristics during region V is subject to a time vary-

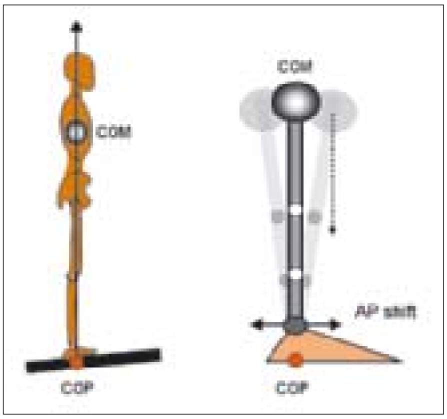

Fig. 5 *Inverted pendulum model of human balance shows that positioning of joint centres is crucial to ensure the system of external joint moments generated about the ankle, knee and hip allows efficient stable standing with minimal muscular control.*

ing velocity vin input and can be characterised according to:

where c is the damping constant and k is the modulus of the spring. The time dependent properties of the actuators throughout angular region V means that for short transient loading events such as heel strike the mechanical response becomes stiffer and more elastic. At lower angular velocities stress is dissipated as the actuator creeps. This „stress relaxation“ behaviour tends to automatically balance moments about the ankle. As such abnormal reaction moments that normally occur when walking on inclines are dissipated and therefore excessive and potentially damaging loading on the socket due to mal-alignment is removed. Due to the passive realignment and inelasticity under loading the orientation of the foot remains slightly dorsiflexed at push off to assist ground clearance during swing phase. The time dependent and variable mechanical stress-strain characteristic throughout the hydraulic range of motion is illustrated in figure 4. This unique mechanical characteristic gives Echelon a time dependent adaptive quality which means abnormal stump interface loading is removed automatically shortly after limb loading.

Self -Optimization of Alignment, Biomimetic control of balance

The upright posture in humans standing means that the centre of gravity of any segment lies more or less above the joint which supports it in a condition of unstable equilibrium. This natural balancing act can be thought of as balancing an inverted compound pendulum as shown in figure 5.

In order to facilitate simulation of a natural style of balance control and to accommodate the non-elastic resilience offered by the ankle the alignment of the ankle joint relative to the body was found to be critically important. The aim was to allow a degree of natural control and optimization of natural standing balance which closely follows the dynamics or inverted pendulum control. The ideal standing posture is one that is safe stable and requires minimal levels of muscular control input. Video vector visualisation of the effects to changes to the AP shift position of the ankle joint centre are shown in figure 6 validating use of use of an inverted pendulum approach to guide shift alignment setup. The shift alignment is easily optimized since the amputee can feel the effect on balance control and advise the prosthetists accordingly.

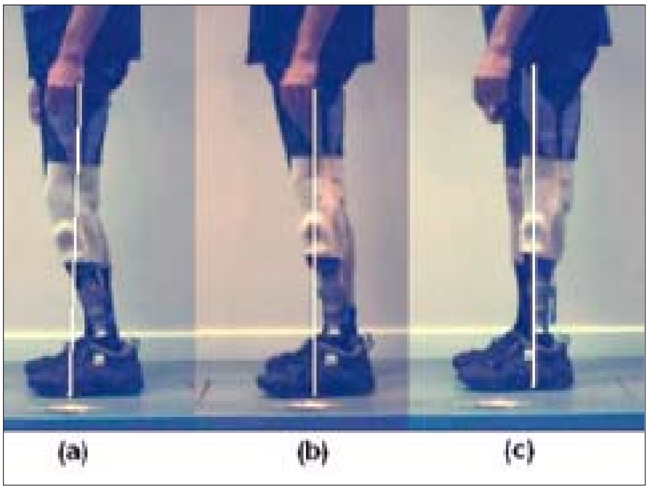

Fig. 6 *Video vector visualisation showing the effect of AP shift alignment on the self-aligning ankle-foot, Echelon. A: ankle joint centre is set too far posteriorly (hyperflexion, causing a sensation of falling forwards), B: the ankle joint position allows a relaxed standing posture with minimal muscular control, C: the ankle joint is set too far anteriorly causing destabilising extension moment (hyperextension, sensation of falling backwards).*

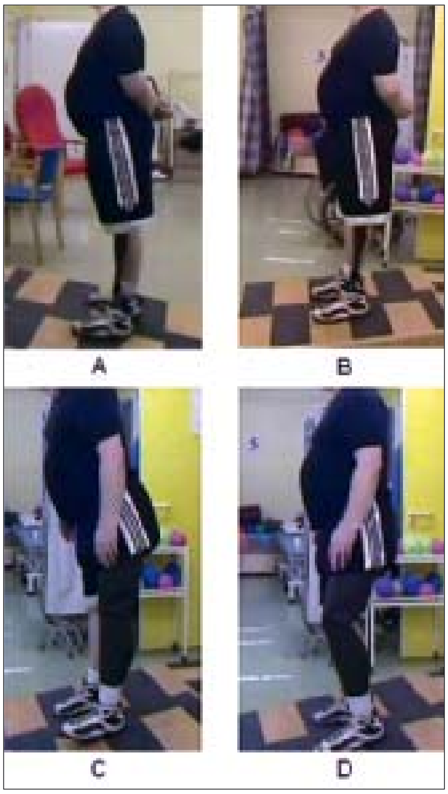

Fig. 7 *Comparison of standing postures on inclines using the self-aligning foot ankle, Echelon (A and B) and a conventional foot, Esprit (C and D). The compensating actions in C and D are self-evident.*

Results and discussion

The unique properties of the Echelon prosthesis means that for the first time amputees can stand with a natural posture on inclined surfaces. An example comparison of standing postures of a trial TF amputee standing on a 12 degree incline is shown in figure 7. Postures A and B were produced using the Echelon foot and the amputee reported that it felt no different to standing on the level. Postures C and D were produced using a conventional foot design (Esprit foot with fixed ankle). With the conventional foot the amputee had great difficulty in standing on the incline and was generally unable to bear significant weight on the prosthetic side. Pylon load cell measurement verified these observations (fig. 8 and 9) highlighting differences in designs in terms of the ability to carry weight (axial load, reported as percentage body weight %BW) through the prosthesis whilst standing on inclines.

Overall the trial results have showed a marked improvement in