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Full Length Article

Dynamic elastic response prostheses alter approach angles and ground reaction forces but not leg stiffness during a start-stop task

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ABSTRACT

In a dynamic elastic response prosthesis (DERP), spring-like properties aim to replace the loss of musculature and soft tissues and optimise dynamic movement biomechanics, yet higher intact limb (IL) loading exists. It is unknown how amputees wearing a DERP will perform in start-stop movements and how altering the prosthetic stiffness will influence the performance and loading. This study assessed movement dynamics through comparisons in spatiotemporal, kinematic and kinetic variables and leg stiffness of intact, prosthetic and control limbs. The effect of prosthetic stiffness on movement dynamics was also determined. Eleven male unilateral transtibial amputees performed a start-stop task with one DERP set at two different stiffness – Prescribed and Stiffer. Eleven control participants performed the movement with the dominant limb. Kinematic and kinetic data were collected by a twelve-camera motion capture system synchronised with a Kistler force platform. Selected variables were compared between intact, prosthetic and control limbs, and against prosthetic stiffness using ANOVA and effect size. Pearson's Correlation was used to analyse relationship between leg stiffness and prosthetic deflection. Amputees showed a more horizontal approach to the bound during the start-stop movement, with lower horizontal velocities and a longer stance time on the IL compared to controls. In both stiffness conditions, the IL showed selected higher anteroposterior and vertical forces and impulses when compared to the controls. Leg stiffness was not significantly different between limbs as a result of the interplay between angle swept and magnitude of force, even with the change in prosthetic stiffness. A main effect for prosthetic stiffness was found only in higher impact forces of the prosthetic limb and more horizontal touchdown angles of the IL when using the prescribed DERP. In conclusion, amputees achieve the movement with a horizontal approach when compared to controls which may reflect difficulty of movement initiation with a DERP and a difficulty in performing the movement dynamically. The forces and impulses of the IL were high compared to control limbs. The consistent leg stiffness implies compensation strategies through other joints.

1. Introduction

Physical activity is important for amputees to gain from the physiological and musculoskeletal health benefits associated with exercise. Though para-sports often require amputees to participate without their prosthesis (wheelchair tennis and basketball, sitting volleyball, football), the review by Deans, Burns, McGarry, Murray, and Mutrie (2012) suggests that amputees would prefer to engage in inclusive, integrated sports wearing their prosthesis. However, amputees perceive that their prosthesis limits their performance

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(Deans et al., 2012).

Passive-elastic prostheses, commonly known as dynamic elastic response prostheses (DERP), have been developed to enable lower limb amputees to run (Nolan, 2008). The principle behind DERP is that the passive-elastic spring is deformed in loading and the stored energy is returned during unloading of the foot, contributing in forward propulsion (Zelik et al., 2011). The ideal prosthetic stiffness should vary according to the speed and dynamics of the movement performed. Currently, a DERP can only return the energy absorbed while in biological limbs, the powerful contraction of the ankle plantarflexors is the primary contributor to propulsive force production (Hamner, John, Higginson, & Delp, 2009) and running speed (Dorn, Schache, & Pandy, 2012). In dynamic non-locomotor movements, where the role of the ankle-foot complex in absorbing and generating the load is modulated depending on the task (Neptune, Kautz, & Zajac, 2001; Zajac, 2002), amputee performance may be compromised due to the passive prosthetic spring, as evidenced in jumping (Schoeman, Diss, & Strike, 2012; 2013). A prosthetic spring that modulates in response to the demands of the movement in a similar way to an intact active ankle is not viable due to weight and material limitations. Manufacturers recommend prosthetic spring stiffness to be based on the weight and activity requirements of the user. However, there is little research to indicate the effect of prosthetic stiffness on the performance of the athlete or on potential injury mechanisms (Butler, Crowell, & Davis, 2003), other than Wilson, Asfour, Abdelrahman, and Gailey (2009), who found that prosthetic stiffness has significant effect on leg stiffness of the intact limb (IL) in a case study of a transtibial amputee male sprinter.

If DERP are to be used in sports, they must allow amputees to complete a variety of dynamic, non-locomotor manoeuvres effectively. Since DERP have been designed for steady state running (Nolan, 2008) and are optimal at the natural frequency of the spring, their performance in other activities may be compromised resulting in undue strain on the IL. Past research on amputee walking and running has suggested that (i) the IL is overloaded compared to the prosthetic limb (PL) (Grabowski et al., 2009; Rossi, Doyle, & Skinner, 1995; Snyder, Powers, Fontaine, & Perry, 1995) and when compared to the biological limb of an able-bodied control group (Baum, Hobara, Kim, & Shim, 2016) as a result of the reduced push-off contralaterally (Morgenroth et al., 2011) and (ii) the increased force is responsible for increased leg stiffness on the IL (Hobara et al., 2013; McGowan, Grabowski, McDermott, Herr, & Kram 2012). How and why the increased loading occurs is unclear due to a number of limitations. Past research has executed the analyses using many different types of prostheses (Baum et al., 2016; Hobara et al., 2013) which may influence the results. Research has been conducted on walking and running with variable step lengths between limbs which results in different velocities at touchdown (TD) and take off (TO). Consequently, the impulse required against the ground is adjusted to ensure ongoing stepping. Finally, the influence of manufactured prosthetic stiffness on the loading and leg stiffness may play a role and has not been assessed.

It is not known how amputees wearing a DERP will perform in start-stop movements common in court-based sports, how the limbs will experience the load to enable the movement and how altering the prosthetic stiffness will influence the performance. To investigate this, we chose a controlled start-stop movement to assess the ability of the amputees to initiate movement, bound forward dynamically on the assessed limb and then stop the movement in a stable erect stance (Fig. 1). We chose to focus on the stance phase of the bound to assess the biomechanics on the intact and prosthetic limbs and the effect of stiffness. As this stance phase will be affected by the initial and terminal conditions, we chose to control these by defining the distances to be achieved in each part of the movement. The purpose of this research in analysing a controlled forward movement is to develop our understanding of mechanisms which underpin movement mechanics and loading in amputees during activities other than walking and running.

Thus, the first aim of the research was to determine spatiotemporal, kinematic and kinetic differences between the IL, PL and control limb (CL) when executing a start-stop dynamic movement using their Prescribed DERP. The second aim was to determine the effect of prosthetic spring stiffness on the movement performance. We hypothesised that there would be no between-limb difference in spatiotemporal (initiation time, stance time, flight time, and movement completion time) and kinematic variables (TD and TO angles, and pelvis velocity) since the controlled nature of the task would require a similar execution. We hypothesised that the kinetic variables (peak vertical and anteroposterior forces and impulses) and leg stiffness (K_{leg}) would be greater on the IL and less on the PL compared to each other and to the dominant biological limb of an able-bodied control group (CL) as a result of the presence of the prosthesis. Finally, we hypothesised that a change in prosthetic stiffness would have no effect on kinematic variables but would increase the loading and leg stiffness variables on the PL and IL.

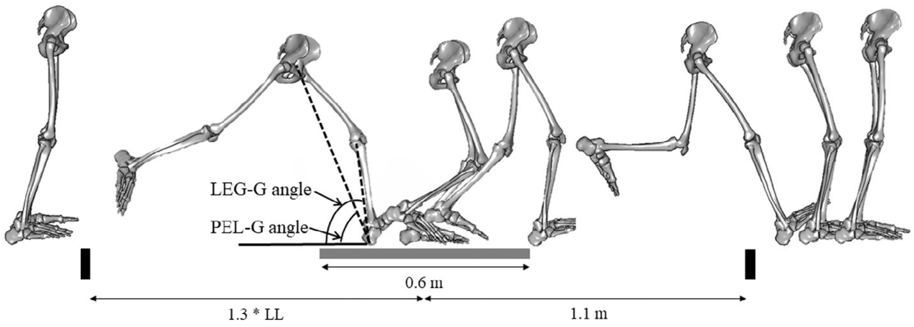

Fig. 1. An illustration of the start-stop task performed by participants in this study. A mark on the floor indicated the initial take off position at a distanced normalized to the participant's leg length (1.3 * LL) to a mark at the centre of the force platform. Distance between this mark and the stop zone, which was marked with tape was fixed at 1.10 m. The participants were asked to land with their heels beyond the stop-zone mark. The LEG-G and PEL-G angles at touchdown are shown.