MODELLING TRANSTIBIAL PROSTHESES FOR SIMULATION

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Investigating the effect of a prosthetics size, shape, and stiffness on sports performance requires a theoretical approach, however this requires a more complex representation of the prosthetic beyond those previously adopted. A chain model was used to investigate the level of complexity (n-segments; n=2,3,4) required to reproduce the kinematics and kinetics of a prosthetic during six different movements performed by a unilateral transtibial amputee athlete. The optimal solution was evaluated using an angle-driven simulation model and close agreement (3% RMS difference) was observed between the simulation and recorded performances suggesting the complexity was sufficient. This approach could be employed within theoretical approaches to investigate the cause and effect of prostheses on sporting movements or to custom fit appropriate prostheses for individual athletes.

KEYWORDS: long jump, angle-driven model, prosthetics, para-athletics

INTRODUCTION: The use of carbon fibre prostheses within sport has become of increasing interest in recent years due to the inability to assess whether their use provides athletes with an unfair advantage compared to able-bodied athletes. While research has predominately focussed on comparing the kinematic and kinetic differences when using prosthetics vs an intact limb during movements (Hobara et al., 2014; Willwacher et al., 2017), this does not aid the understanding of the effect of the size, shape, and stiffness of prosthetics on the performance of sporting movements. Current practice for manufacturers is to recommend prostheses using subjective stiffness categories based on the height and weight of the user rather than the activity it is required for. Although the size, shape and stiffness of prosthetics has been investigated experimentally, limitations within the study design may impact the reliability of these findings (Beck et al., 1996; Taboga et al., 2020). To understand the effect of the size, shape, and stiffness of a prosthetic on the performance of different sporting movements requires an approach such as computer simulation modelling where parameters can be controlled for consistency (McErlain-Naylor et al., 2021). To adopt this approach, a representation of the prosthetic with sufficient complexity allowing accurate kinematics and kinetics to be produced is required. The purpose of this study therefore was to evaluate a method which determines the level of complexity required to accurately reproduce the kinematics and kinetics of a transtibial prosthesis during different sporting movements.

METHODS: Kinematic and kinetic data were collected from a Paralympic long jumper (age: 34 years, mass: 53.9 kg, height: 1.68 m) using an Össur (Reykjavik, Iceland) Cheetah Xtend prosthesis in an indoor high-performance centre. An 18 camera (MX13) Vicon system (300 Hz) synchronised with an AMTI force plate (3000Hz) was used to capture the athlete and prosthesis under six different loading activities: unloaded, walking, hopping, running, 9-stride approach long jump, and a 17-stride approach long jump. Seventy-six reflective markers were placed on the athlete, of which, twenty-eight were placed mediolateral of the blade and socket such that their mid-points corresponded with the centre of the blade or residual limb. Each pair was located such that it coincided with a turning location of the blade identified as the apex of regions where the curve of the blade tightened via visual inspection. The data was processed in Vicon’s Nexus software and exported to MATLAB for analysis. The marker trajectories located on the prostheses were filtered at 4Hz using a 4^{th} order Butterworth filter determined via residual analysis (Winter, 1990). The blade was split into nine-segments with the distal and proximal ends coinciding with the mid-point of the marker pairs (Figure 1). Length-time histories of each segment were determined to identify segments in which intra-segment deformation occurred using a 2 mm threshold. Angle-time histories between successive segments were also calculated to identify where the blades turning points were located.

To determine the appropriate number of segments required to accurately represent the prosthesis an optimisation algorithm was used. Firstly, the sections of the blade, where the inter-segment angle-time histories were approximately constant were removed from the optimisation problem and represented using rigid segments with a fixed angle between them. For the rest of the blade, the coordinates of the markers in this section were translated into the sagittal plane and a cubic spline was used to interpolate between them to provide the shape of the blade. Chain models comprising of 2, 3 and 4 segments were then fit to the interpolated data using a simulated annealing algorithm which varied the length and orientation of each segment to minimise the distance between the chain model and the interpolated data at three time points (first, last and time of maximum compression) from each of the five different loading activities. To evaluate the optimised solution for each chain model, a simulated annealing algorithm was used to minimise the distance between the chain model and the interpolated data for all time points by varying the orientation of each segment for the activity with the highest ground reaction force (17-stride approach long jump). In addition, a chain model using the lengths from the unloaded static trial was also compared to determine whether this optimisation process was necessary.

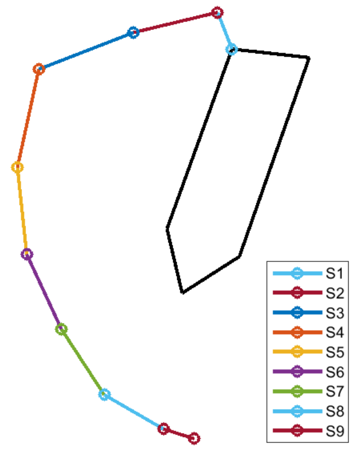

Figure 1: Segmentation of the blade (names sequential from stump to toe)

A planar 18-segment angle-driven computer simulation model of the take-off stride of long jump for a transtibial athlete was constructed using Autolev^{TM} (Kane & Levinson,1985) to determine the viscoelastic properties of the blade. Ten rigid segments represented the body: head + trunk, two upper arms, two forearms + hands, two thighs, two shanks, one foot, with wobbling masses within the shank (non-residual), thighs and trunk. Based on the results of the methods described above, eight rigid segments were used to represent the blade with the joints between segments either angle-driven (fixed angle) or torque-driven using viscoelastic torsional springs. The blade had four points of contact with the ground and viscoelastic springs were used to represent the foot-ground interface. The model was customised to the participant using subject-specific inertia parameters (Yeadon,1990) and the inertia of the prosthesis was determined using a geometric approach. A common set of 36 viscoelastic parameters were varied via a genetic algorithm to minimise an objective function representing the difference between simulation and three recorded performances (hopping, running and 17-stride approach long jumping). The object function was an average of an RMS score given to each of the three matched simulations consisting of the differences in five components: force; centre of mass velocity; blade joint angles; time; and trunk orientation angle. Each difference was weighted equally, and one degree was equivalent to 1% difference in other measures. Penalties were employed to limit horizontal slide and vertical compression of the blade during impact as well as the movement of the wobbling masses.

RESULTS & DISCUSSION: There were no distinct patterns in the length of any of the segments across any of the different loading activities indicating that there was minimal intra-segment bending and it is appropriate to represent each segment rigidly. Minimal changes in the S1-S2, S7-S8 and S8-S9 inter-segment angles were found suggesting it was suitable to minimise these segments with a fixed angle (see Figure 1 for definitions). While similar patterns of change (inverse parabola) were found in the inter-segment angles S2-S3, S3-S4, S5-S6, S6-S7 with larger angular displacements occurring with higher loading. This suggests that a chain model with either 2, 3 or 4 segments was suitable to accurately replicate the prosthetic.

Table 1: RMS differences between chain models and interpolated blade marker data

	2-segments	3-segments	4-segments	4-segments*
Matching (mm)	2.9	1.1	0.8	1.0
Evaluation (mm)	4.0	1.3	1.0	0.9
Mean	3.5	1.2	0.9	1.0

* 4-segment chain model using lengths from unloaded trial

The difference between each chain model and the recorded performance data reduced with increase complexity (Table 1). A large reduction was shown to occur between 2-segments and 3-segments suggesting the adoption of a simple spring model isn't appropriate. Similar results were also observed for the 3-segment and 4-segment chain models and the results were consistent when evaluated using the whole 17-stride approach long jump performance (Table 1). These results indicate that both the 3-segment and 4-segment models provide accurate representations of the blade. Interestingly, the segment length and joint locations of the 3-segment chain model corresponded to locations within the structure of the blade where the carbon fibre thickens. Since this is likely to be correlated with changes in blade stiffness, an 8-segment representation was used which incorporated the 3-segment chain model within the angle-driven simulation model with the following segments: S1, S2, C1, C2, C3, S6, S7, S8, S9 (where C1-C3 are the 3 segments determined via optimisation).

Table 2: RMS scores for the three matching simulations with component differences

Component	Hop	Run	Jump	Mean
Force (%)	4.6	6.7	6.9	6.1
COM velocity (%)	3.3	4.0	2.9	3.4
Trunk orientation (°)	0.5	0.5	0.6	0.5
Blade angles (°)	0.8	1.7	1.7	1.4
Time (%)	2.9	1.6	3.7	2.7
RMS (%)	2.9	3.6	3.8	3.4

The common set of viscoelastic parameters, determined by concurrently matching three movements with differing levels of loading, were seen to provide close agreement, 3.4%, with individual performance scores for: hopping: 2.9%; running: 3.6%; and jumping (17-stride approach long jump): 3.8% (Table 2). The average score of 1.4% for the difference in the blade angle-time histories between the simulated and recorded performances indicates that the 8-segment representation of the blade provides sufficient complexity to reproduce the kinematics of the prosthesis under different loads (Figure 2). The key features of the force-time histories were maintained (Figure 3) with an average difference score of 6.1% considered good agreement. The differences between the simulated and recorded horizontal ground reaction force (Figure 3) is potentially due to using pin-joint model approach which introduces problems associated with a lack of compliance throughout the system (Allen et al., 2012), using the raw force data within the matching, or potential force plate vibration. Due to the good agreement this approach was deemed suitable to reproduce the kinetics of the prosthesis during different loading activities.

The close agreement between the simulations and the recorded performance indicates that the 8-segment representation is complex enough to accurately model a transtibial prosthesis whilst under load. The validity of the method of fitting a chain model to the recorded performance data to determine the required complexity of the model and using an angle-driven approach to determine the viscoelastic properties provides a potential method for representing other prostheses. It should be noted however that further research is required to determine the robustness of this method for other prosthetics and to investigate the correlation between the size, shape and viscoelastic properties of the blade and the manufacturer's stiffness rating.

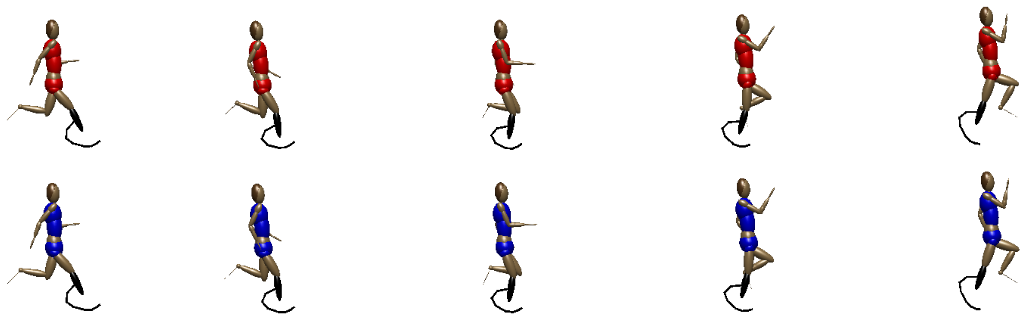

Figure 2: Comparison between long jump performance (top) and matched simulation (lower).

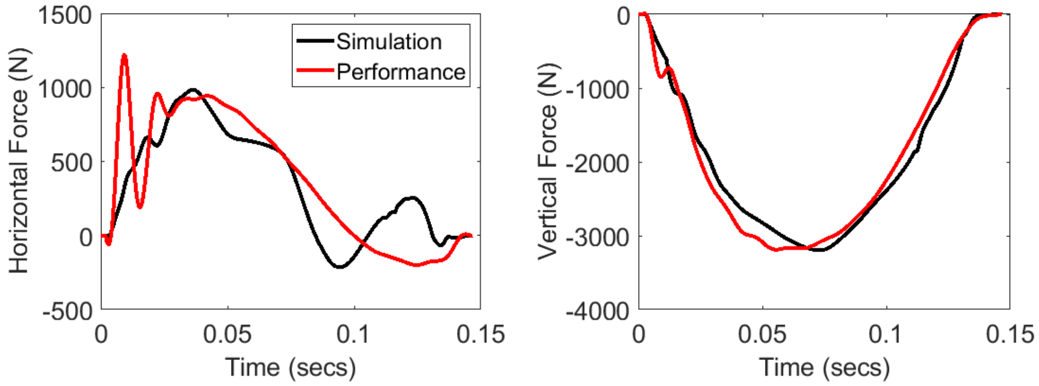

Figure 3: Comparison of vertical and horizontal ground reaction forces for long jump performance and simulation.

CONCLUSION: This study has identified and evaluated a method which determines the complexity required to accurately reproduce the kinematics and kinetics of a transtibial prostheses during movements with different loading patterns. In the future, this method could be employed within a forward-dynamics computer simulation model to investigate the cause and effect relationships of movements in transtibial amputees. This method could also be used to individualise the fitting of prostheses especially for athletes where the prosthesis is likely to heavily impact performance. This would substantially improve the current process which subjectively recommends a prosthesis based on the height and weight of the recipient. For example, custom prosthesis could be designed, or a best-fit approach could be undertaken where an athlete is matched to existing prostheses using premeasured blade parameters.

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