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Skill assessment in upper limb myoelectric prosthesis users: Validation of a clinically feasible method for characterising upper limb temporal and amplitude variability during the performance of functional tasks

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Upper limb myoelectric prostheses remain challenging to use and are often abandoned. A proficient user must be able to plan/execute arm movements while activating the residual muscle(s), accounting for delays and unpredictability in prosthesis response. There is no validated, low cost measure of skill in performing such actions. Trial-trial variability of joint angle trajectories measured during functional task performance, linearly normalised by time, shows promise. However, linear normalisation of time introduces errors, and expensive camera systems are required for joint angle measurements.

This study investigated whether trial-trial variability, assessed using dynamic time warping (DTW) of limb segment acceleration measured during functional task performance, is a valid measure of user skill. Temporal and amplitude variability of forearm accelerations were determined in (1) seven myoelectric prosthesis users and six anatomically-intact controls and (2) seven anatomically-intact subjects learning to use a prosthesis simulator over repeated sessions.

(1): temporal variability showed clear group differences ($p<0.05$). (2): temporal variability considerably increased on first use of a prosthesis simulator, then declined with training (both $p<0.05$). Amplitude variability showed less obvious differences. Analysing forearm accelerations using DTW appears to be a valid low-cost method for quantifying movement quality of upper limb prosthesis use during goal-oriented task performance.

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1. Introduction

As a result of concerted efforts over recent decades, there have been significant advances in myoelectric prostheses design. The motors used have become smaller and more powerful, cosmetic covers have become more life-like, and, of most note, multi-functional hands, such as the i-Limb (Touch Bionics, Livingston, UK) and Be-Bionic (Steeper, Leeds, UK) have been developed. Yet, prosthesis users are still greatly limited by the available control modalities and lack of sensory feedback from the prosthesis [1]. Hence it is not surprising that such devices remain challenging to use and are often poorly utilized, or rejected [2,3]. As more expensive multi-function myoelectric prostheses have become available, such as the i-limb full hand and i-limb digits (Touch Bionics, Livingston, UK), there is an urgent need for well-validated and robust quantitative measures that allow for informed selection of a particular technology (to achieve a better match between user and device), and that have the potential to inform user training.

Currently, quantifying the effectiveness of a given device, or the proficiency with which it is used, remains limited by the available outcome measures [4].Clinical tests often capture self-reported capabilities (e.g. Orthotics and Prosthetics Users' Survey "OPUS" [5]), evaluate performance subjectively (e.g. Assessment of Capacity for Myolelectric Control [6]), or measure speed of performance of a pre-defined set of tasks (e.g. Southampton Hand Assessment Procedure "SHAP" [7]). Research has discussed the limitations with

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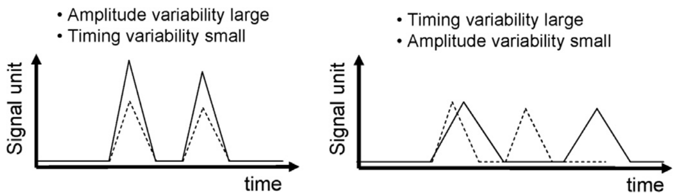

Fig. 1. Illustration of temporal and amplitude variability.

many of these measures, such as reliance upon self-report and/or observer ratings [8–10]; self-report does not directly measure the person's physical capabilities and can be influenced by subject bias, and observer-dependent measures are susceptible to (inter-/intra-) rater bias, which inherently reduces reliability compared to performance-based measures in which the administrator does not form part of the instrument. Previous research has also shown that whilst important [10], speed of task completion is only one of several factors which characterise skilled prosthetic use; other measures, notably gaze and kinematics may further enhance our understanding of user performance and skill level [11].

Accordingly, Major et al. [12] recently compared the kinematics of myoelectric prosthesis users and able-bodied controls without known pathology. Specifically, considering that motor variability (motor variance across task repetition) has shown to decrease with skill acquisition [13,14], and given the redundant degrees of freedom (DoFs) in the upper body musculoskeletal architecture that permit various task-equivalent motor strategies, Major et al. [12] focused on studying kinematic variability of these DoFs. Their results showed that joint kinematic variability is higher in prosthesis users than controls, and was correlated with years of experience of prosthesis use. Their findings suggest that increased compensation may be reflected in increased joint kinematic variability above able-bodied individuals.

In common with almost all studies of upper limb functional task performance, in [12] joint angle trajectories were calculated as follows. Angle trajectories were first linearly normalised with respect to time, and joint level kinematic variability was defined as the variability around a kinematic profile averaged across multiple time-normalised trials. The standard deviation and coefficient of multiple determination then served as outcome measures to characterize variability and repeatability, respectively. However, non-cyclic kinematics are subject to two different aspects of trajectory variability: temporal and amplitude variability (Fig. 1). Specifically, the relative duration of different phases of a given functional movement can vary from trial to trial, and linear time normalization of the entire task cannot take this into account [15]. Hence, while these traditional measures can inform on overall differences in movement variability, they remain limited in that they do not consider temporal variability separately to variations in signal amplitude, yet this has shown to be advantageous in the assessment of non-cyclic functional upper limb tasks [15,16].

Thies et al. previously introduced a novel methodology based on dynamic time warping (DTW) for curve registration across multiple trials to calculate measures of amplitude and timing variability over entire trajectories of functional movements [15]. In their approach a chosen target signal is warped to a declared reference signal by compressing or stretching the target signal along the time-axis with respect to the reference signal in a non-uniform manner. Warp Cost reflects the amount of time-warping needed to achieve the best possible temporal match between curves and serves as a measure of temporal variability. Following the time warping of signals, RMS error then informs on amplitude variability. Separating out temporal from amplitude variability is of particular advantage during processing of non-cyclic upper limb kinematics: we take the stand that DTW is a more appropriate method to analyze kinematic inter-trial variability of the upper limbs during functional task performance since it minimizes the mismatch of the different movement components (Fig. 2).

A first demonstration of the DTW method involved characterization of acceleration trajectories derived from an arm-worn accelerometer during performance of two daily-living activities in subjects with stroke and matched controls. Findings showed increased timing variability for the stroke subjects as compared to controls, and this outcome was reliably reproduced on a second test day one month later [15]. This finding of increased variability following stroke was consistent with numerous previous studies, which have generally used simpler tasks and discrete, rather than continuous, measures of variability (e.g. variability of end point error in pointing tasks) [17,18]. A more recent study used the DTW method to demonstrate differences in trajectory variability when comparing stroke survivors with right and left hemisphere lesions, as well as to healthy controls [16]. They showed increased timing variability in the paretic arm of stroke survivors with right compared with left hemisphere lesions and further confirmed previous finding [15] of increased variability following stroke compared with controls. The DTW method which assesses contributions of temporal and amplitude variability separately proved particularly suitable to identify differences between left and right hemispheric stroke survivors.

Although already demonstrated for assessment of upper limb kinematics in people with stroke, the potential and validity of this methodology to characterise upper limb movements in relation to functional performance for upper limb prosthesis users has yet to be explored. Hence this paper reports on the characterization of functional task performance with an upper limb myoelectric prosthesis using the DTW method. The purpose of this retrospective study was to investigate whether DTW is a valid tool for assessing temporal and amplitude variability of upper limb prosthesis kinematics through a known-groups assessment (Study 1) and a responsiveness assessment (Study 2).

2. Methods

In study 1, we investigated the use of DTW to characterise upper limb function of myoelectric prosthesis users and anatomically intact (AI) controls and its ability to discriminate between these two groups, based on temporal and amplitude variability. In Study 2, we report on the changes in temporal and amplitude variability with practice in using a myoelectric prosthesis simulator (AI subjects), to assess if DTW can identify changes in temporal and amplitude variability resulting from practice of goal-oriented tasks. Since accelerometers are wearable, inexpensive and clinically-accessible devices, we here apply DTW to simulated accelerometer trajectories derived from position data, however, the method is applicable to a range of kinematic data, including joint angle trajectories and data from other segment-mounted inertial measurement units.

2.1. DTW for assessment of temporal and amplitude variability

As previously described elsewhere [15], the DTW method employed in these two studies utilized dynamic programming [19] to separately quantify timing and amplitude variability across multiple trials. Using custom software in Matlab (Mathworks, Natick, MA, USA), the algorithm first time-warps a chosen target signal to a declared reference signal by compressing or stretching the target signal along the time-axis with respect to the reference signal in a non-uniform manner. Warp Cost is returned as a unitless measure indicating the amount of time-warping needed to achieve the best possible temporal match between curves. Warp Cost is

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