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DETERMINING THE NEUROMECHANICAL ROLE OF THE TIBIALIS ANTERIOR MUSCLE IN MAINTAINING BALANCE.

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INTRODUCTION

Human upright stance, despite requiring little cognitive attention to maintain, is a mechanically unstable posture. To maintain this position, the central nervous system (CNS) must integrate information from various sensory sources and subsequently generate corrective torque about the ankle joint [1]. Although the CNS dynamically adjusts the weighting of each sensory signal based upon the situational context under normal conditions, it is believed that healthy people generally rely heavily on proprioceptive signals from the plantar flexor musculature [2,3]. In particular, it has traditionally been thought that the muscle spindles of the primary agonists during standing, the triceps surae, are a main source of this sensory information [3].

Recent evidence however, has shown that the contractile element of these muscles are decoupled from sway position, largely due to a highly compliant tendon, high short range stiffness and significant amount of efferent activity modulation required to generate corrective torque [4,5]. This suggests the CNS may have difficulty extracting an accurate sensory signal from the plantar flexors regarding sway position. As such, recent research has focused on the potential sensory role of the main antagonist during standing, the tibialis anterior (TA) muscle. The fascicles of the deep compartment of TA have been shown to follow sway position closely, suggesting its spindles are well placed to monitor ankle joint position during quiet standing [5].

The present study therefore aimed to progress this earlier study by determining the activation and length change of TA and its fascicles while standing under a range of postural conditions. Specific focus was on the similarity or difference of three discrete anatomical regions of TA. It was hypothesised that during quiet standing, each region of TA would act similarly, with fascicle length changes of each region being positively correlated with ankle joint displacement (postural sway), commonly termed 'orthodoxical' movement [5]. It was speculated that this positive coupling might be lost as postural conditions become more challenging and require forces to be generated by the TA, which could stretch the elastic tendon tissues.

METHODS

Subjects were asked to stand in a comfortable position on a hard, flat surface. In this position, subjects completed two blocks of seven 60-s balance trials. For each block, subjects

completed four different balance conditions, presented in a pseudo-random order, designed to challenge balance differently. The conditions included two trials each of quiet standing with either eyes open (EO), eyes closed (EC), a trial while standing on a reduced base of support (RBOS) as well as one trial of active, voluntary sway. Subjects were given approximately 60s of rest between each trial to avoid possible fatigue effects.

A 3D motion capture system was used to capture sway related kinematic variables, of which, ankle angle (AA) was chosen as the measure of postural sway. Muscle activity (EMG) was recorded using in-dwelling fine-wire electrodes inserted into each region of the TA (proximal superficial, TA_{PS}; proximal deep, TA_{PD}; and distal superficial, TA_{DS}). Muscle fascicles in each region were visualised using B-mode ultrasound and their length subsequently tracked using a custom written algorithm. All data was synchronized to a common time signal.

The mean amplitude and standard deviation (SD) of each kinematic variable, including fascicle length, were calculated to describe sway related changes. The root mean squared (RMS) was calculated for each EMG signal before being normalised to the EMG RMS of a standardized maximum voluntary effort (MVE), recorded prior to the standing trials. All data was grouped according to trial condition and analysed using a two-way analysis of variance. AA was cross-correlated with both the fascicle length and EMG RMS of each muscle region, for each trial, on a time period of $\pm 1.5s$. Cross-correlation analyses were grouped by both muscle region and condition.

RESULTS AND DISCUSSION

Initial group analysis of both AA and fascicle length revealed an increase in SD and amplitude of the AA and fascicle length changes with increasing postural demand (e.g. Figure 1). Similar results were seen in EMG RMS levels for each TA region, suggesting that both sway, fascicle length changes and muscle activity each progressively increased as postural conditions became more challenging.

The grouped cross-correlation analyses showed consistent orthodoxical muscle behaviour between AA and fascicle length movement for the three normal standing conditions (EO, EC and RBOS) and each muscle region. For each region and condition combination, a peak positive

correlation occurred at a zero phase time shift, and was moderate in strength (~ 0.45 ; e.g. Figure 2). The shape of each grouped cross-correlation was similar between conditions and muscle region, with only minor differences in strength observed. During active voluntary sway, all measures were more variable such that the grouped analyses did not exhibit a clear peak correlation.

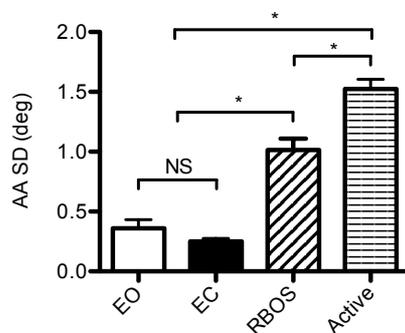


Figure 1: Ankle angle (AA) standard deviation (SD) for each balance condition. Significance is denoted by * and non-significance by NS.

The results of the present study confirm the initial hypothesis that the TA acts in an orthodox manner during quiet standing, thus placing it in a favourable position to provide accurate sensory information regarding sway position. This behaviour held true for both the EO and EC conditions, where TA activation levels were relatively low ($\sim 4\%$ of MVE). It was also true for each muscle region, confirming further expectations that there would be no differences between discrete regions of TA. Surprisingly however, this orthodox behaviour also existed for the challenging RBOS condition, where a slightly larger activation of the TA was required ($\sim 7\%$ of MVE), which we initially hypothesised would act to decouple fascicle length changes from postural sway driven AA changes. Such decoupling was confirmed in the active sway condition, where the activation observed was larger again ($\sim 18\%$ of MVE), and a consistent relationship (orthodox or paradoxical) between fascicle length and AA was not found.

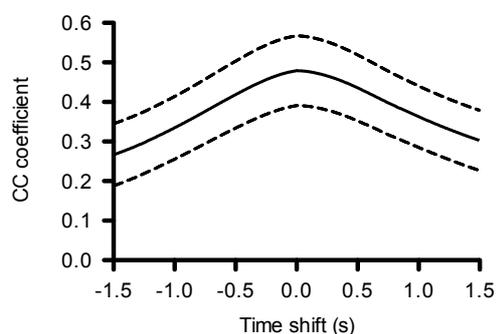


Figure 2: Grouped cross-correlation analysis of the relationship between the ankle angle (AA) and proximal, superficial fascicle length (TA_{ps}) changes of the TA.

The present results support the speculation of the potential proprioceptive role of TA in balance control. This is driven by the moderate positive correlation between fascicles in the deep compartment of the TA and postural sway during normal standing. That similar observations were found in

each region of the TA is in contrast with the earlier study, possibly related to slight anatomical vagaries or ultrasound tracking differences. Nonetheless, these results do build upon suggestions that TA is well placed to provide proprioceptive information regarding sway position [4,5]. Despite having a long, compliant tendon and aponeurosis [6], the amount of activity in TA during quiet standing is low, allowing for sway driven changes in the total muscle-tendon unit (MTU) to be reflected in proportional length changes of its contractile fibers. It is therefore likely that the extrafusal muscle spindle fibers, that convey muscle length and velocity information to the CNS, would also follow fascicle movement and as such, Ia-afferent signals originating from TA would be appropriately coded to give an accurate depiction of sway position. Such information would be integrated with other afferent signals at the spinal and/or higher levels of the CNS for maintaining balance.

As expected, when subjects were asked to voluntarily generate postural sway in the active sway condition, TA fascicle length change was decoupled from AA displacement in most subjects. This is similar to observations in the plantar flexors, whereby the contractile stiffness of the muscle is increased, which, in combination with a compliant tendon, leads to overall length changes that are largely taken up by the tendon rather than the fascicles [4]. As such, despite the total MTU length of the TA being positively correlated with AA, it is likely that due to increased TA activity, MTU length changes are not reflected by movement of the fascicles and therefore TA spindles. This resonates with recent broad suggestions that actively modulating muscles may be less able to accurately represent sway position and as such the CNS may preferentially use less active and less modulated muscles [7], or potentially shift its focus towards other sensory sources such as the vestibular, visual or other somatosensory systems [2].

CONCLUSIONS

The present study provides further evidence that TA is well placed to act as a quiet listener of sway position during quiet standing. Due to its low levels of activity in normal standing, its muscle fascicles change length in line with sway driven ankle angle changes that allow its spindles to accurately transmit sway position. It is likely that Ia-afferent activity from the TA spindles is subsequently used by the CNS to help monitor and maintain balance. In tasks where greater TA activation is required, such as the active sway task, the orthodox relationship of fascicle length change with sway position is lost, likely due to the increased contractile stiffness in the muscle, which sees most of the MTU length change take place in the compliant tendon, thereby rendering the proprioceptive function of TA spindles less effective

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