VARIABILITY ANALYSIS OF WALKING WITH CONTINUOUSLY INCREASING ASSISTANCE FROM A SOFT EXOSUIT

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INTRODUCTION

Recently, multiple groups showed that it is possible to reduce the metabolic cost of walking with portable exoskeletons [1,2] or exosuits [3]. While these devices could be used for overground walking they still have to be further optimized to become more practically useful. Studies from the field of exercise physiology suggest that optimization protocols with continuous parameter changes can be less time consuming and allow to investigate more parameter settings than steady state protocols. However, when using this method for optimizing a wearable device it could be that the additional actuation variability perturbs the wearer. In fact, studies with robotic ankle prostheses have suggested relationships between actuation variability and metabolic cost [4]. To understand the isolated effect of continuously changing actuation magnitude we compared results from a condition where actuation magnitude continuously increased versus a condition with steady-state actuation.

METHODS

7 participants walked on a treadmill at 1.5 m s^{-1} wearing a soft exosuit that assists plantarflexion and hip flexion (Figure 1A). The assistance profile used position control to achieve different target peak forces [5]. In a *ramp* condition, the target peak force delivered at the ankle continuously increased from 0 to 75% body weight over 10 minutes (Figure 1B). In a *step* condition, participants walked in a series of five-minute steady-state conditions with five target peak forces between 0 and 75% of body weight [6,7]. At the end of each gait cycle the exosuit controller slightly modified the amount of retraction of the cable for the next gait cycle based on the error between the desired and the actual peak force. While this iterative control scheme tries to minimize the error in the peak force based on each previous gait cycle it does not predict the effect of the human variability for the next gait cycle. The actual peak forces are a result of the motor position as well as human kinematics. So if the controller remains the same then changes in peak force variability indicate changes in human variability. To evaluate the evolution of inter-stride variability in the peak force during the *step* conditions as well as the entire *ramp* condition, we calculated inter-stride standard deviation over a moving window of 30 strides [7]. However, it is expected that some portion of this standard deviation is due to the slope of the *ramp* rather than an intrinsic increase in variability. In order to evaluate variability isolated from the slope of the *ramp* we also calculated the 30-stride standard deviation of the first-difference as described in [7]. To compare these two types of variability metrics between the *step* and *ramp* conditions we fitted the results with second order polynomial regression versus peak assistive force and evaluated significance differences at the five force levels of the *step* condition.

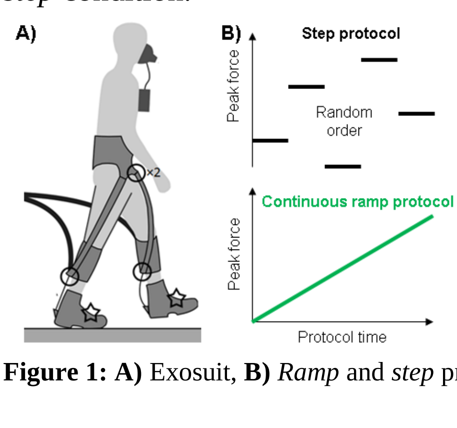

Figure 1: A) Exosuit, **B)** *Ramp* and *step* protocol

RESULTS AND DISCUSSION

Figure 2A shows higher inter-stride standard deviation in assistive peak force over a moving window of 30 strides in the *ramp* conditions at the lowest two force levels. However, after de-trending using the first difference method there were no more significant differences between the *ramp* and *step* condition (Figure 2B). This absence of increased variability after detrending for *ramp* slope suggests that participants were not perturbed by the slow linear increase peak force. This echoes results from a recent split-belt study where it was assumed that participants are well capable at tracking treadmill speed perturbation changes when they are implemented in a gradual way as in the *ramp* condition [8].

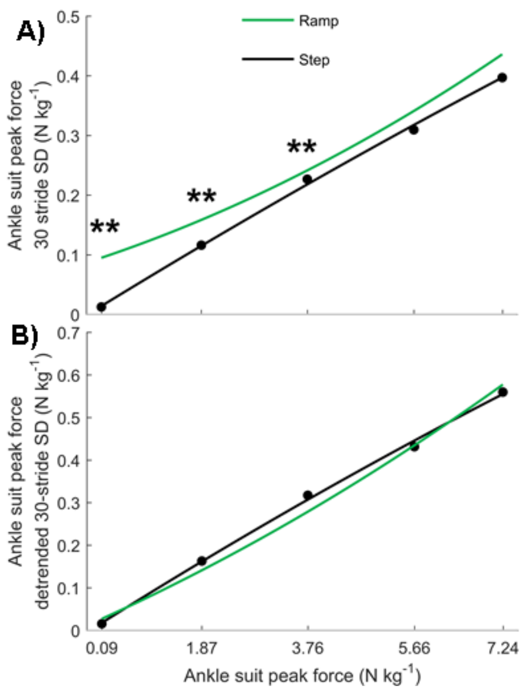

Figure 2: Inter-stride variability of ankle suit peak force. A) Standard deviation over a 30-stride window. **B)** Standard deviation after detrending using the first-difference method [7]. (** $p < 0.01$)

CONCLUSIONS

The variability analyses shown here indicate that a slow continuous parameter change does not cause additional biomechanical variability. Consequently, such continuous parameter sweep can also be used as a faster alternative than a discrete *step* protocol for mapping variability as a function of actuation parameter values. In separate analyses, however, we have found that metabolic results can be different between a continuous parameter sweep and discrete *step* protocol [6]. Future analyses involving non-linear variability measures as described in [9, 10] could be useful to further investigate if there are changes in variability between continuous *ramp* sweeps and discrete *step* protocol.

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