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Short communication

Changes in relative work of the lower extremity joints and distal foot with walking speed

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ABSTRACT

The modulation of walking speed results in adaptations to the lower limbs which can be quantified using mechanical work. A 6 degree-of-freedom (DOF) power analysis, which includes additional translations as compared to the 3 DOF (all rotational) approach, is a comprehensive approach for quantifying lower limb work during gait. The purpose of this study was to quantify the speed-related 6 DOF joint and distal foot work adaptations of all the lower extremity limb constituents (hip, knee, ankle, and distal foot) in healthy individuals. Relative constituent 6 DOF work, the amount of constituent work relative to absolute limb work, was calculated during the stance and swing phases of gait. Eight unimpaired adults walked on an instrumented split-belt treadmill at slow, moderate, and typical walking speeds (0.4, 0.6, and 0.8 statures/s, respectively). Using motion capture and force data, 6 DOF powers were calculated for each constituent. Contrary to previously published results, 6 DOF positive relative ankle work and negative relative distal foot work increased significantly with increased speed during stance phase ($p < 0.05$). Similar to previous rotational DOF results in the sagittal plane, negative relative ankle work decreased significantly with increased speed during stance phase ($p < 0.05$). Scientifically, these findings provide new insight into how healthy individuals adapt to increased walking speed and suggest limitations of the rotational DOF approach for quantifying limb work. Clinically, the data presented here for unimpaired limbs can be used to compare with speed-matched data from limbs with impairments.

1. Introduction

The effective modulation of walking speed results in adaptations by the lower limbs which can be quantified using various gait parameters. Recognizing that the flow of energy gives rise to movement, analyses to quantify lower limb adaptations with speed are ideally suited to use the principles of energy, work, and power.

Biomechanical joint work has historically been calculated using a sagittal (1 degree-of-freedom (DOF) rotational) or 3 DOF (all rotational) approach. Teixeira-Salmela, et al. calculated positive and negative joint work as a percentage of absolute sagittal limb work (summed positive and absolute negative work of the hip, knee, and ankle) over the entire gait cycle (Teixeira-Salmela et al., 2008). The researchers found the relative percent contribution of both positive and negative ankle work decreased with increased walking speed, while the hip and knee contributions increased, suggesting the hip flexor muscles assist with limb forward progression. These findings were consistent with relative joint work calculations over stance phase only (Chen et al., 1997). Farris and Sawicki used 3 DOF data to calculate the percent average positive joint power relative to the total average positive power of the limb over a stride (Farris and Sawicki, 2011) and found that positive relative joint average power did not differ across speeds.

Recently, Zelik et al. utilized a 6 DOF approach to determine changes in lower limb work with speed (Zelik et al., 2015a). The analysis used 6 DOF power calculations for the hip, knee, and ankle joints (Buczek et al., 1994) and the inclusion of a distal foot segmental power term (Siegel et al., 1996). (The term "constituent" will be used throughout this manuscript to refer to the hip, knee, and ankle joints and the distal foot segment.) A 6 DOF approach, which includes joint translations unlike the 3 DOF approach, is currently the most comprehensive means for analyzing the energy

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changes of the system. Summing the constituent work to generate a measure of 6 DOF limb work, Zelik et al. found that both positive and negative 6 DOF limb work increased with speed (Zelik et al., 2015a). However, it remains unclear if the relative constituent contributions to the absolute 6 DOF limb work adapt by increasing proportionally with walking speed.

We used 6 DOF work calculations of the four lower limb constituents to quantify the relative constituent work, or the percentage of positive or negative work each constituent contributed to absolute 6 DOF limb work, across a stride, revealing the primary constituent "drivers" and "brakers", respectively. Work at the joint and segmental levels is defined here as a measure of energy generation (positive) and dissipation (negative) (e.g. by muscles). However, it is noted that inverse dynamics calculations of work do not account for co-contraction, work done by two-joint muscles, partition of energy stored in elastic structures versus muscle, or heat dissipation (Purkiss and Robertson, 2003; Umberger and Martin, 2007). Relative constituent work can be meaningful for characterizing how constituent contributions to gait change throughout the gait cycle and how these contributions are affected by speed. The objective of this study was to quantify the speed-related 6 DOF work adaptations of all the lower extremity limb constituents in healthy individuals.

2. Methods

A subset of previously reported data (Goldberg and Stanhope, 2013) was used for data analysis. Briefly, eight healthy adult subjects (height 1.77 ± 0.08 m, mass 71.8 ± 15.5 kg) walked on an instrumented treadmill (Model TM-06-B, Bertec Corp., Columbus, OH) while kinematic and force platform data were collected. All subjects provided informed consent under IRB protocol. Reflective markers were placed on subjects using a modification to a previously reported marker configuration (Holden et al., 1997) and a six-camera motion capture system was used to collect kinematic data (Vicon, Los Angeles, CA).

Subjects walked at three stature-scaled speeds (0.4, 0.6, and 0.8 statures/s, ranging from approximately 0.7 to 1.4 m/s), which will be denoted as slow, moderate, and typical walking speeds, respectively. All conditions were randomized, and subjects were given sufficient time to acclimate to each condition (approximately 1.5–2 min) (Donelan and Kram, 1997). Motion capture data were sampled at 120 Hz and low-pass filtered at 6 Hz, and treadmill force data were sampled and low-pass filtered at 1040 Hz and 10 Hz, respectively.

Using Visual3D software (C-Motion, Inc. Germantown, MD), 6 DOF constituent powers were calculated using published methods (Buczek et al., 1994; Takahashi and Stanhope, 2013). The stance phase of gait was defined as the period over which the vertical ground reaction force exceeded a threshold of 20 N. Power data were scaled by body mass and averaged across strides for each condition within subjects, with a minimum of five strides per condition. Left leg stance (heel-strike to toe-off) and swing (toe-off to heel-strike) data for clean strides are presented.

Positive and negative constituent work values were calculated for each subject by integrating the respective portions of the constituent power curves over stance and swing phases. Absolute 6 DOF limb work (${}^{abs}W_{limb}$) was the sum of the positive and absolute value of the negative 6 DOF limb work over both stance and swing (Eq. (1)). Relative work (RW) was the absolute value of each constituent's work divided by the absolute 6 DOF limb work as a percent (e.g., negative relative ankle work in Eq. (2)). Absolute relative work was the sum of the positive and negative relative work contributions for that constituent. Each work value was scaled by body mass and averaged over all subjects at each speed.

$$\begin{aligned}{}^{abs}W_{limb} = {} & ({}^{+}W_{hip} + {}^{+}W_{knee} + {}^{+}W_{ankle} + {}^{+}W_{distal\ foot})_{stance} \\ & + |({}^{-}W_{hip} + {}^{-}W_{knee} + {}^{-}W_{ankle} + {}^{-}W_{distal\ foot})_{stance}| \\ & + ({}^{+}W_{hip} + {}^{+}W_{knee} + {}^{+}W_{ankle})_{swing} + |({}^{-}W_{hip} + {}^{-}W_{knee} + {}^{-}W_{ankle})_{swing}| \end{aligned} \quad (1)$$

$${}^{-}RW_{ankle} = (|{}^{-}W_{ankle}| / {}^{abs}W_{limb}) * 100\% \quad (2)$$

Differences in relative constituent work were compared separately across the three walking speeds using several three-way and two-by-three way repeated measures ANOVAs with an overall p value of 0.05. All post hoc comparisons reported have been adjusted using the Bonferroni correction using SPSS software (IBM Corp., Armonk, NY). Due to violating sphericity a number of times, a more conservative Greenhouse-Geisser adjustment was used. For the ankle, knee, and hip, the repeated measures ANOVAs took into account two phases (stance and swing) and three speeds (slow, moderate, and typical). A significant phase-by-speed interaction indicates that the way in which relative work changed with speed depends on the phase (stance or swing). If a phase-by-speed interaction was significant, then pairwise comparisons at each phase for the three speeds were examined. For the distal foot, the repeated measures ANOVA compared the major effect of only speed (slow, moderate, and typical) and not phase; distal foot calculations are not applicable in swing since the foot does not contact the ground.

3. Results

Power curves for each constituent are shown in Fig. 1. Absolute 6 DOF limb work over a gait cycle significantly increased with walking speed ($p < 0.001$): 0.93 ± 0.20 J/kg, 1.28 ± 0.25 J/kg, and 1.66 ± 0.31 J/kg for slow, moderate, and typical speeds, respectively (all $p < 0.001$). Average relative constituent work values with standard deviations are represented in bar charts in Fig. 2. Table 1 lists the means and standard deviations for relative constituent work values (J/kg) during stance and swing.

There were no noteworthy trends in the few significant pairwise comparisons for the hip and knee across speeds in the two phases. For ${}^{+}RW_{ankle}$ and ${}^{-}RW_{ankle}$, there were significant phase-by-speed interactions ($p = 0.005$ and 0.001, respectively). In stance, ${}^{+}RW_{ankle}$ significantly increased with speed ($p = 0.022$, slow-moderate; $p = 0.014$, slow-typical; $p = 0.011$, moderate-typical). The ${}^{-}RW_{ankle}$ significantly decreased with speed in stance ($p = 0.023$, slow-moderate; $p = 0.005$, slow-typical; $p = 0.005$, moderate-typical). The ${}^{-}RW_{distal\ foot}$, significantly increased with speed in stance, ($p = 0.018$, slow-moderate, $p < 0.001$, slow-typical; $p = 0.013$, moderate-typical).

4. Discussion

The purpose of this study was to use 6 DOF calculations of work to identify lower limb constituent adaptations that occur with increased walking speed. In healthy individuals without lower limb impairments, constituent work relative to absolute limb work calculations identified that primarily the relative work contributions of the ankle and distal foot in stance change with increases in walking speed (Fig. 2).

Relative constituent work characterizes how constituent contributions to gait change throughout the gait cycle, as well as how these contributions are affected by speed. In stance, the positive relative ankle work and negative relative distal foot work increased while the negative relative ankle work decreased with speed (Fig. 2). Interestingly, the absolute relative ankle work did not significantly differ with speed while the absolute relative distal foot work did significantly increase during stance (supplemental Table A). The ratio of positive to negative relative work of the combined ankle-foot across speeds never exceeds 1, which supports previous findings that the combined ankle-foot acts similarly to a spring in terms of net energy storage and return (Takahashi and Stanhope, 2013).

A post hoc analysis found that the ratio of positive ankle work to negative distal foot work was similar across speeds (1.51, 1.58, and 1.57 for slow, moderate, and typical). This may suggest some coupling of the ankle-foot system. Similar coupling was found in a recent study where researchers used a footplate to artificially restrict metatarsal joint extension and decrease negative distal foot work which resulted in decreased positive ankle work (Arch and Fylstra, 2016). The compensation of work by either the ankle or foot when the other is restricted may be a result of a motor coordination strategy by the brain to maintain smooth and steady walking. However, others are investigating this coupling from a biomechanical approach to determine how the activity of the long toe flexors relates to ankle plantar flexor power during late stance (Honert and Zelik, 2016; Zelik et al., 2015b). An understanding of whether a portion of the negative distal foot work is dissipated or transferred as positive work to the ankle joint by long toe flexors