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Asymmetric walking on an incline affects aspects of positive mechanical work asymmetrically

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A R T I C L E I N F O

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A B S T R A C T

The purpose of this study was to determine the extent to which we could use a split-belt experimental paradigm to increase limb or joint work. Split-belt treadmill walking was combined with uphill walking at 0°, 5° and 10° in young, healthy individuals to assess whether we could specifically target increased force output between and within limbs. Thirteen healthy, young adults participated in this study. Participants performed walking trials with the left belt at 1.0 m/s and the right belt at 0.5 m/s. Repeated measures ANOVAs assessed the effects of speed of the treadmill belt and incline on total and joint specific positive extensor work as well as relative work. Mechanical work varied because of the speed and incline of the treadmill belt at the level of the total limb and across joints. Positive lower extremity relative joint work varied as a result of treadmill belt speed and treadmill incline. Positive mechanical work was greater on the limb that was on the faster treadmill belt, regardless of incline. Increases in relative knee but not hip joint work increased as incline increased. The current investigation shows that the nervous system can shift mechanical work production both between and within limbs to safely walk in a novel split-belt environment. This work extends previous research by demonstrating that researchers/clinicians can also use increasing treadmill incline (or some other means to add increased resistive forces) during split-belt treadmill walking to encourage increased mechanical output at particular limbs and/or joints which may have rehabilitation implications.

1. Introduction

Walking in complex environments requires that individuals have the capacity to alter joint work to meet the external demands of the task (Hurt and Grabiner, 2015; Kuhman and Hurt, 2019b). Amongst other things, capacity to alter joint work allows humans to quickly adapt gait mechanics when walking terrain changes (e.g., hills vs flat, grass vs. concrete surfaces). Because such changes are regularly encountered in community settings, the capacity to alter joint work is an important component for safe and efficient ambulation. Decreased capacity to alter joint work of the motor system could decrease mobility (Kuhman et al., 2018; Kuhman and Hurt, 2019b; Kulkarni et al., 2021; Rosenblatt et al., 2020) and limit function. Altering the external mechanical demand of a walking task and quantifying subsequent changes in kinetic outputs of lower extremity joints may offer a diagnostic tool for assessing the capacity of the nervous system to flexibility alter joint work based on task demands. Moreover, creating a novel challenge that the nervous system must overcome may provide an indication of how this flexibility may be manipulated to improve motor functioning with intervention (Rosenblatt et al., 2020).

Experimental paradigms that intentionally disturb usual gait mechanics away from normal conditions can provide insight into the flexibility of the nervous system while increasing symmetrical joint work between limbs. For instance, walking at a self-selected speed, against increasing forces parallel to the treadmill surface (via treadmill incline or backward directed resistive forces) results in an increase in positive lower limb work to overcome the external constraint of the task (Hurt et al., 2020; Hurt et al., 2015; Naidu et al., 2019). Although total positive work scales at the limb-level, the distribution of work across the three major lower extremity joints does not scale in a similar fashion. In fact, compared to the ankle and knee, positive work at the hip increases at a greater rate to overcome increased external work while walking uphill or walking against resistive force (Conway et al., 2018; Nuckols et al., 2020) resulting in greater relative increases in positive joint work

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(Kuhman and Hurt, 2019b). However, others have shown that young adults maintain similar relative contributions of lower extremity joint work across speeds (Farris and Sawicki, 2012). Increased contribution of the hip to locomotor function may be specific to the external constraints of the task performed.

Walking over a level, obstacle-free surface typically results in the performance of symmetric joint work between limbs that is stereotyped and specific to the phase in the gait cycle and the external constraints of the task. However, walking outdoors or in the community may require asymmetric increases in work to meet task demands. For instance, stepping up onto a curb or walking along an uneven surface creates asymmetric demands that require asymmetric adaptations by the neuromuscular system. In this regard, one limb may have to do more of the total work for forward progression and this positive work may be generated at different intralimb joints based on the constraints of the task. In this context, it is important for researchers and clinicians to consider methods for assessing one's ability to appropriately modify lower extremity kinetics in response to asymmetric external demands. Split-belt treadmill walking can be used to create an asymmetric walking environment, as it increases mechanical demand of the limb on the faster treadmill belt (Roemmich et al., 2012; Sanchez et al., 2019). While many mechanical adjustments to split-belt walking are explained by the speed of the treadmill belt, some alterations may not be intuitive. For instance, the limb on the slower belt generates a larger knee joint moment during the typical braking phase (Roemmich et al., 2012). The increased knee moment corresponds with the contralateral limb on the faster belt creating a larger propulsive ankle joint moment. This asymmetric joint work is necessary to keep oneself centered on the treadmill. Thus, split-belt treadmill walking not only creates between-limb asymmetries in mechanical demand, but also between joint asymmetries between each limb.

The human neuromuscular system can modify kinetic output to meet external task demands that relate to speed, increased external work, and split-belt treadmill walking. In order to meet the external demand, mechanical work can be disproportionately shared between the two limbs and across different joints within each limb (Kuhman and Hurt, 2019b). The purpose of this study was to determine the extent to which we could use a split-belt treadmill walking environment to create conditions that result in increased limb or joint work. We combined split-belt treadmill walking with increasing treadmill incline in young healthy individuals to assess the ability to specifically target increased force output between and within limbs. We hypothesized that the limb on the faster belt would generate higher total limb work regardless of the treadmill incline and that hip work would bilaterally increase in relative percent of total work with speed and incline compared to other joints.

2. Methods

Thirteen healthy, young adults participated in this study (mean age: 25.3; mean height: 1.72 m; mean mass: 72.27 kg). Individuals were excluded if they had any lower extremity injury within 6 months prior to participation. All participants provided written, informed consent prior to performing the protocol approved by the Institutional Review Board of the University of Alabama at Birmingham. Kinematics were collected by placing thirty-eight reflective markers on specific anatomical landmarks to define and track body segments with a 9-camera motion capture system sampling at 100 Hz (Vicon, Oxford EN). Individuals walked on an instrumented dual-belt treadmill that measured ground reaction forces sampling at 1000 Hz (Motek, Amsterdam, BG). All data were time synced through Vicon Software and tracked offline and post-processed in Visual 3D (C-motion, Germantown, MD) and MATLAB (MathWorks Inc., Natick, MA).

Participants performed walking trials under belt speed configurations in the following order: both belts tied at 0.5 m/s, both belts tied at 1.0 m/s, and the belts split, with the left belt at 1.0 m/s and the right belt at 0.5 m/s. After each two-minute split-belt trial the participant walked with the belts tied at 1.0 m/s as a "washout" trial. Individuals then walked over the lab floor for 5 min and confirmed that they felt symmetrical when walking and visually appeared to have returned to a normal gait pattern to further ensure "washout". These conditions were performed in the order listed above at 0°, $+5^\circ$, and $+10^\circ$ of treadmill incline. Thus, each participant performed a total of nine walking trials. At each incline we recalibrated the lab coordinate system to align the vertical axes normal to the treadmill. Brief periods of rest were provided between each trial. For the current analysis we provide data on the split-belt conditions with added incline to address our hypotheses.

2.1. Data analysis

We used the last 20 steps of each trial for analysis. Kinematics and kinetics were lowpass filtered at 6 Hz and 12 Hz respectively using a 4th-order zero lag Butterworth filter. An inverse dynamic routine quantified sagittal plane joint moments and powers at the hip, knee, and ankle using commercial software (Visual 3D, C-motion inc., Germantown MD). Positive joint work was then quantified as the integral of positive joint power:

$$U_{joint} = \int_{t1}^{t2} P_{joint} dt$$

Total positive limb work was quantified by summing lower limb work of the hip, knee and ankle (Farris and Sawicki, 2012).

$$U_{total} = U_{hip} + U_{knee} + U_{ankle}$$

Kinetics were normalized to body mass of participants. To quantify how relative positive work was modified with treadmill incline in a split-belt treadmill environment, individual positive joint work was divided by the total positive limb work multiplied by 100.

$$R_{joint} = \left(\frac{U_{joint}}{U_{total}}\right) \times 100$$

To test the hypotheses, repeated measures ANOVAs were used to assess the effects of treadmill belt speed (0.5 and 1.0 m/s during split-belt), incline (0°, $+5^\circ$, and $+10^\circ$), and their interaction on limb work and on positive and relative work at each joint. Thus, we ran four separate ANOVAs: limb, hip, knee, and ankle. At the limb level, U_{total} was compared across the two limbs and three inclines. For each of the three joints, U_{joint} and R_{joint} were compared across the two limbs and three inclines. Bonferroni post-hoc pairwise comparisons on significant main effects were used to assess effects of limb or incline on our dependent variables. A p-value of <0.05 was set for significance. For post-hoc comparison's adjusted p-values are listed.

3. Results

Qualitatively, the extent to which kinetics were modified as individuals walked in the split belt conditions were first assessed. As can be observed (Fig. 1), modifications that occurred over time were small relative to the work generated under the constraints of the protocol.

Limb and joint-level mechanical work varied as a result of both belt speed and incline during split-belt treadmill walking (Fig. 2). For total positive limb work, the incline × belt speed interaction was not significant ($p = 0.439$), however main effects of incline ($p < 0.001$) were significant, whereby total positive limb work incrementally increased from 0° to 10° (adjusted $p < 0.001$, for all comparisons except 5 to 10°, adjusted $p = 0.023$) and the limb on the faster belt generated greater positive work compared to the limb on the slower belt ($p < 0.001$). At all three joints, we observed significant belt speed × incline interactions (hip: $p = 0.03$; knee: $p < 0.001$; ankle: $p = 0.025$, Fig. 3). For positive hip work, a significant main effect of incline was observed ($p < 0.001$). As incline increased, hip work increased (0° to 5°, adjusted $p < 0.001$; 0° to 10° adjusted $p < 0.001$), however no significant difference was detected

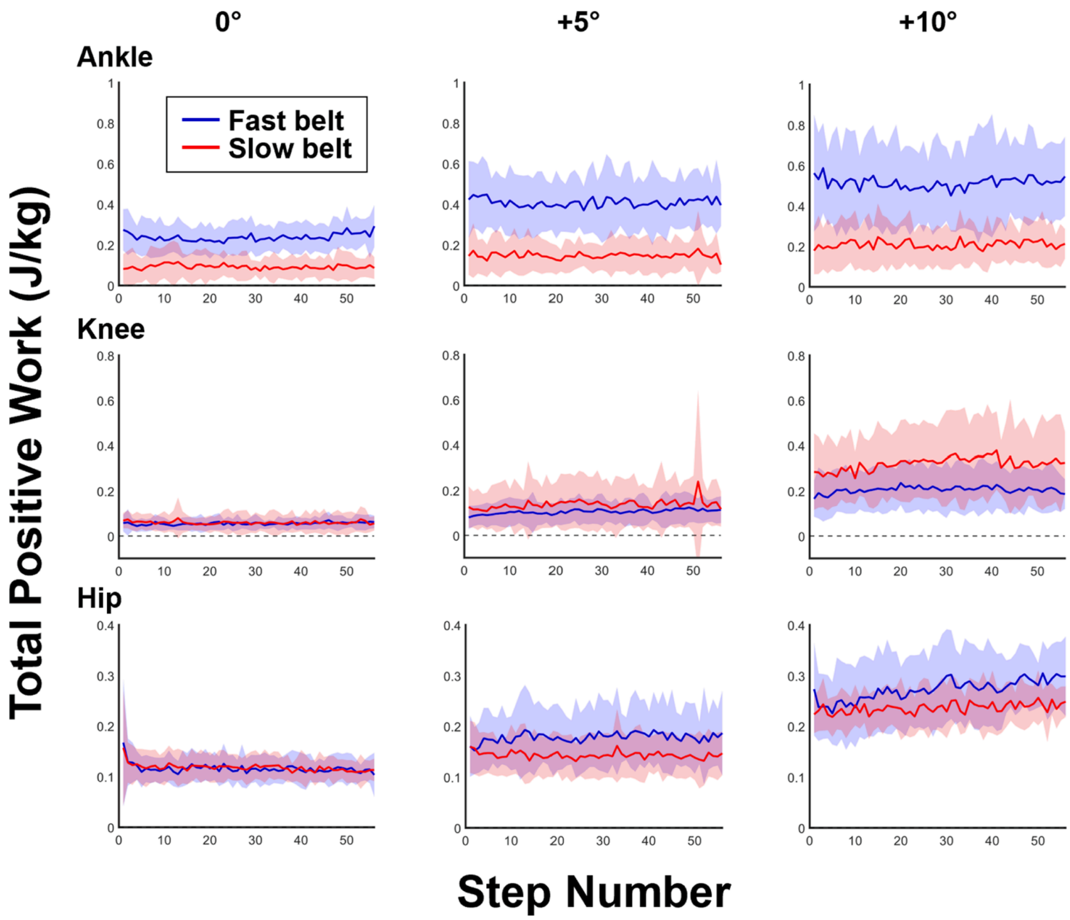

Fig. 1. Summary data for all participants of mechanical work from the ankle, knee, and hip as they walked for two minutes in a split-belt treadmill environment. Group level data from the limb on the faster belt (blue, 1.0 m/s) and the slower belt (red, 0.5 m/s) is displayed along with the standard deviation (shaded area). Qualitatively, the change in mechanical output across steps is small relative to the variability in the measures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

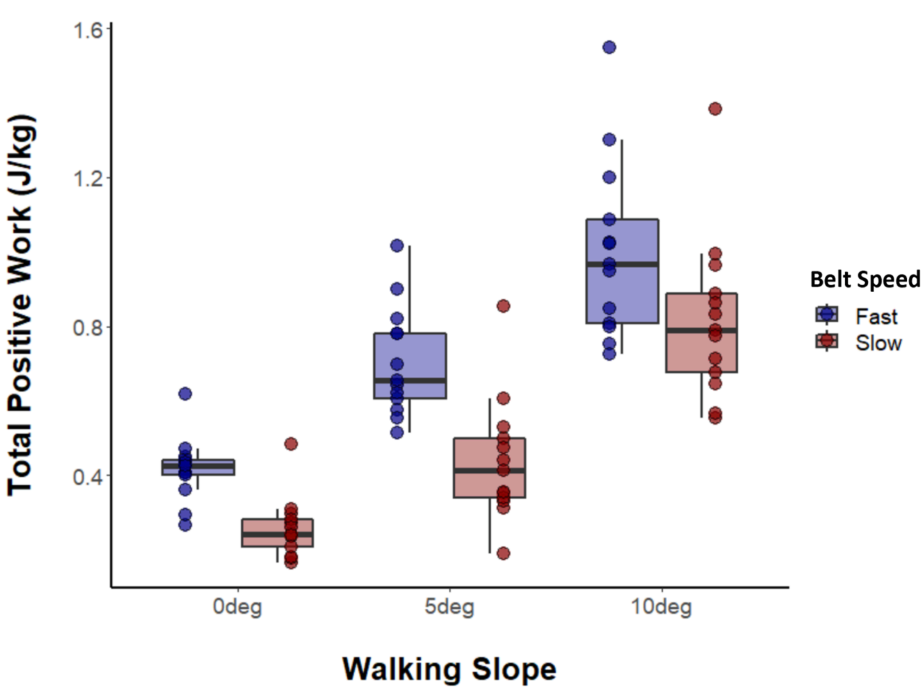

Fig. 2. Box and whisker plots of lower limb extensor positive work between limbs and across the different treadmill inclines is displayed. Individual data points are overlayed. Data from the limb on the faster belt (blue, 1.0 m/s) and the slower belt (red, 0.5 m/s) is displayed. The limb on the fast belt generated significantly more positive mechanical, although both the limb on the fast and slow belt produced greater mechanical work. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

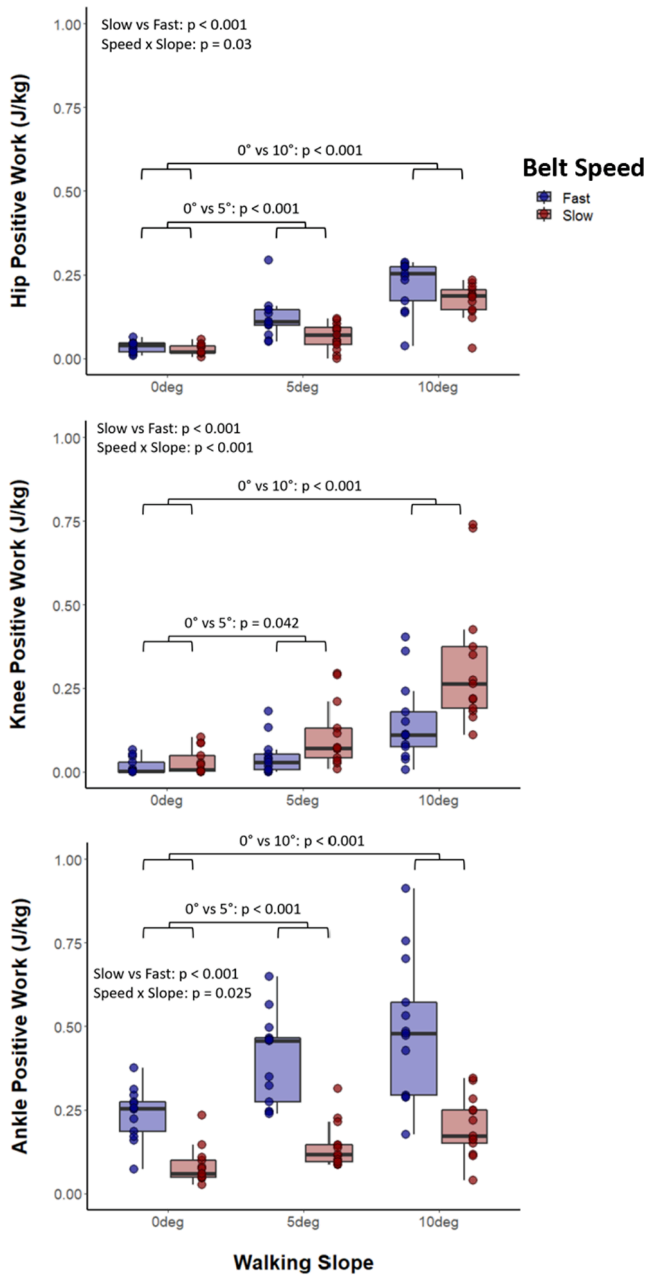

Fig. 3. Box and whisker plots of lower limb extensor joint work of the hip (top) knee (middle) and ankle (bottom) between limbs across the different treadmill inclines is displayed. Individual data points are overlayed. Data from the limb on the faster belt (blue, 1.0 m/s) and the slower belt (red, 0.5 m/s) is displayed. Significant interactions were observed for the hip and knee, but not the ankle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between the two incline conditions (5° to 10°, $p = 0.161$). Greater positive hip work was generated by the limb on the faster belt speed ($p < 0.001$). A significant main effect of incline was observed for knee joint work ($p < 0.001$). As incline increased, knee work increased (0° to 5°, adjusted $p = 0.042$; 0° to 10°, adjusted $p = 0.001$). However, no significant difference was detected between the two incline conditions (5° to 10°, $p = 0.119$). Greater positive knee work occurred on the slower belt ($p < 0.001$). For ankle positive work a significant main effect of incline was observed ($p < 0.001$). As incline increased, ankle work increased (0° to 5°, adjusted $p < 0.001$; 0° to 10°, adjusted $p = 0.001$) but did not significantly differ between the two incline conditions (5° to 10°, $p = 0.374$). Greater positive ankle work occurred on the faster belt (adjusted $p < 0.001$).

Relative joint work varied as a result of belt speed and treadmill incline (Fig. 4). We observed a significant interaction between treadmill belt speed and incline at the hip ($p = 0.009$). The main effect of treadmill belt speed was significant ($p = 0.001$) with greater relative work at the hip for the limb on the slow belt, while the main effect of incline was not significant ($p = 0.073$). A significant interaction was detected at the knee ($p = 0.007$) and main effects of belt speed ($p < 0.001$) and incline ($p = 0.001$) were also significant. Positive relative knee joint work on the slower belt accounted for more of the total limb work as incline increased compared with positive knee joint work on the faster belt. A significant interaction was not detected between speed and incline for the ankle ($p = 0.500$). Main effects of speed ($p < 0.001$) and incline ($p = 0.003$) were significant. More relative work at the ankle occurred on the faster belt and relative ankle work for both belts decreased with incline.

4. Discussion

In this investigation, we show that split-belt treadmill walking can be combined with treadmill incline to increase bilateral positive limb work. In support of our first hypothesis, positive work was greater for the limb that was on the faster treadmill belt, regardless of incline. We did not support our second hypothesis; increases in relative percent of joint work of knee but not hip joint work increased as incline increased. This work extends previous research on split-belt treadmill walking by investigating the extent to which speed and increased incline of the treadmill modify limb- and joint-level work.

The finding that positive work increases with treadmill belt speed and incline is not surprising. Walking at faster speeds requires increased positive lower limb work (Farris and Sawicki, 2012; Kuhman et al., 2018; Silder et al., 2008) to propel the center of mass at a faster rate of movement. Walking uphill also requires increased work on the center of mass, not only to propel the body forward, but also to lift the center of mass step by step (Nuckols et al., 2020). However, it is not obligatory that the introduction of a split-belt treadmill-walking environment would necessarily result in combinatory increases observed independently with incline and treadmill belt speed. The neuromuscular system needs to solve the imposed asymmetry of gait while also increasing kinetic output based on the increasing treadmill incline (Sombric et al., 2019). For instance, the limb pushing off the faster belt coincides with the lead limb generating a braking force on a slower belt, so the work performed in double stance is no longer approximately equal and opposite (Sanchez et al., 2019; Selgrade et al., 2017) like typical walking (Kuhman and Hurt, 2019a). For individuals to avoid falling off the front or back of the treadmill, the nervous system must quickly modulate forces that allow the body to perform the external work required by the task. This tradeoff could manifest as an interaction with increasing treadmill incline (Sombric et al., 2019). However, the addition of increasing treadmill incline resulted in a parallel increase in total positive lower limb work for both limbs whose output was also scaled to the speed of the treadmill belt. As a means for using the described paradigm for training, clearly the combination of speed and incline can be used to increase limb work, depending on the goal of the intervention. While the limb on the slow belt generates less positive work than the limb on the faster belt, the addition of just 5 degrees can result in positive joint work on the slow belt that is comparable with the positive work generated on the fast belt at 0° (Fig. 2).

Increases in positive joint work while walking on a split-belt treadmill with increasing incline, challenges the neuromuscular response to meet the constraints of the task. Compared to walking on a flat treadmill, adding incline resulted in greater positive work for all joints. Positive joint work of the hip and ankle increased to a greater degree on the faster belt with increasing treadmill incline. For the hip and ankle, the greatest increase in positive work occurred on the faster belt. Indeed previous research has suggested that the hip joint acts to augment increasing walking speed with respect to the ankle joint work as a complementary

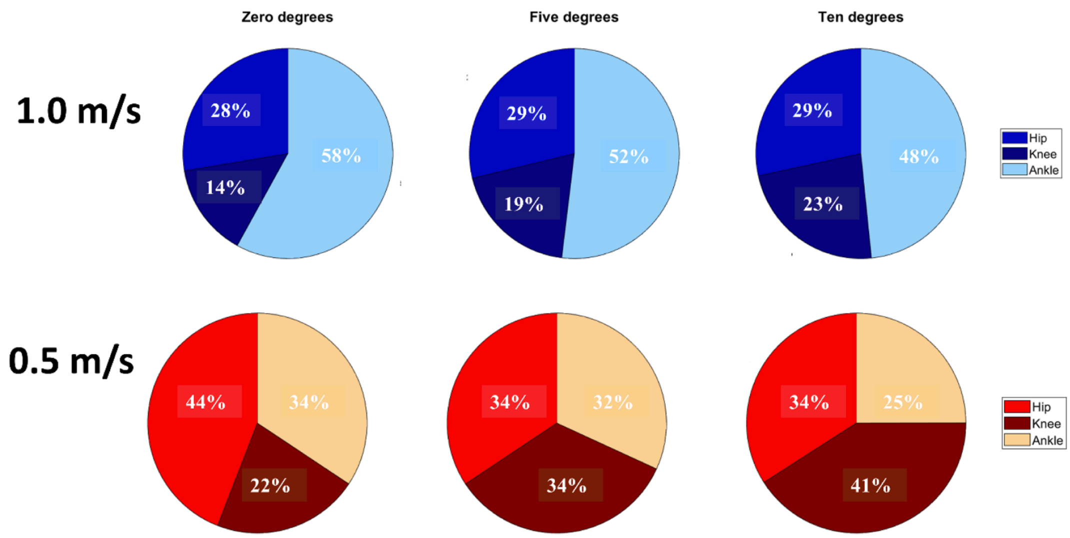

Fig. 4. Relative percentage of total positive mechanical work of the lower extremities relative to the limb on the faster (1.0 m/s, Blue shades) and slower (0.5 m/s, Red Shades) treadmill belt. With incline the we observed a significant increase in knee joint work on the slower belt ($p < 0.001$) while the hip and the ankle generated greater relative joint work on the faster treadmill belt ($p < 0.001$ for both comparisons). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

action of these relatively large extensor muscles (Oh et al., 2012). Traditionally the ankle and hip are the primary mechanical motors (i.e., they generate positive mechanical work) while walking uphill, thus, this finding appears intuitive. However, the results for the knee joint were not completely intuitive. Increases in positive knee joint work occurred for the limb on the slow belt as treadmill incline increased. During normal walking the primary function of the knee is as a mechanical damper performing negative work during stance (Kuhman and Hurt, 2019b) and thus plays a relatively small overall role in generating positive work to propel the center of mass even at increasing walking speeds (Holden et al., 1997). While walking within a split-belt environment, an asymmetric strategy in propelling the center of mass has been observed between the slow and fast belt, which has been suggested to be driven by energetic consequences of walking in a split-belt environment (Selgrade et al., 2017). The increases we observed in knee work while increasing the incline of the treadmill surface are consistent with previous work where increases in positive work of the knee joint are observed even at slower walking speeds (Kuhman and Hurt, 2019b; Montgomery and Grabowski, 2018), where the knee functions more as a mechanical motor to raise the center of mass on a step to step basis (Kuhman and Hurt, 2019b). Our results complement a previous investigation that showed that compared to walking faster on level ground, walking uphill at a slower speed resulted in similar knee joint kinetics (Haight et al., 2014).

The use of split-belt walking paradigms has in both clinical and basic science contexts has increased in recent years. Within a clinical context, promising results have been reported from the use of split-belt treadmill walking as a therapeutic approach to reduce gait asymmetry for patient populations such as stroke and Parkinson's (Reisman et al., 2007, 2009; Roemmich et al., 2014), though some methodological questions remain to aid translation (Lewek et al., 2018). A potential approach to augment split belt treadmill walking is adding increasing external forces through incline or applied resistive forces. These forces can be added via increased treadmill incline, similar to the present study (Sombric et al., 2019; Sombric and Torres-Oviedo, 2020) or using backward resistive forces while walking to increase the amount of external work that needs to be overcome while walking on the treadmill (Conway et al., 2018; Hurt et al., 2020; Hurt et al., 2015; Naidu et al., 2019). These added external increase the mechanical work needed to walk at a fixed speed without necessitating increasing the treadmill speed, which may be challenging for individuals with lower reserve speed (i.e., maximum-comfortable walk speed) (Wang et al., 2015).

The present work has certain limitations that should be discussed. Individuals walked under the split-belt condition for a total of two minutes each trial, which may preclude adaptation of the gait pattern to reach a steady state performance. Indeed, investigations using variables such as step length suggest that adaptation may continue to occur after more than 40 min while walking in a novel split-belt environment (Sanchez et al., 2019). While these findings are significant, it should be noted that the modifications to step length symmetry are relatively small after the first 50 steps (Reisman et al., 2007) and previous research has shown that adaptations with the addition of hill walking actually hasten adaptation(Sombric et al., 2019). Further, in the current investigation, we were interested in kinetic adaptation and show minimal changes in kinetics relative to the variability of these measures (Fig. 1), which seems reasonable given the changes in step length symmetry that occur are relatively small spatial changes. Only one split-belt condition (belt speed ratio of 2:1) was used. It would be of interest to see if a bigger split in the speed between belts would accentuate the changes we report. The number of participants in the study is relatively small. However, the results we present were similar in pattern across all participants, suggesting this phenomenon may be generalizable across young healthy adults. Finally, the order or presentation of trials was not randomized. It has been reported in numerous investigations that changes to kinematic variables such as step length occurs during the first trial and this effect lessens upon repeated exposures (Kuhman et al., 2022; Leech et al., 2017), which appears to scale based on the difference in belt speeds (Leech et al., 2017). However, we report minimal changes in kinetic trends over our two-minute trials, so we are unable, without the benefit of further study, to assess the extent to which order affects the changes we observed in joint level kinetics by participants.

The current investigation extends previous research in split-belt treadmill walking and increasing treadmill incline by demonstrating that researchers/clinicians can target particular limbs and/or joints to increase joint-related mechanical work. Our previous work has suggested that individual joints can perform different functions (i.e., spring vs. motor) depending on the external constraints of the task performance, which suggests that joints can be trained to perform whatever function is required to walk within a given environment. However, depending on the level of data individuals are interested in, or the purpose of the training, clinicians or researchers may modify which limb is on which belt, particularly if the individuals experience orthopedic or neurological constraints that result in asymmetric gait.

CRediT authorship contribution statement

Christopher P. Hurt: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Daniel J. Kuhman:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **William R. Reed:** Writing – review & editing, Writing – original draft, Validation, Resources. **Andrew Baumann:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Wei Jiang:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Katherine Marsh:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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