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Investigation of a passive inter-limb device on step-to-step transition of human walking

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***Abstract*—In walking like an inverted pendulum, the step-to-step transition period requires a substantial amount of simultaneous positive and negative mechanical work to redirect the center of mass between steps and it was considered as a major determinant of gait in terms of metabolic expenditure. In the current study, we developed a passive inter-limb device that transfers energy between the legs during the step-to-step transition period. By effectively transferring the energy dissipated at heel-strike from the leading leg to the trailing leg which is performing push-off, we hypothesize that the mechanical cost of transport (COT) will be reduced. Consequently, the lower limb muscles are required to do less positive and negative work, resulting in a reduced metabolic COT. Data from five subjects walking at 1.2m/s on an instrumented treadmill with the device active and passive was collected. It was found that the mechanical COT during the step-to-step transition period was reduced when walking with the device active. However, contrary to our hypothesis the metabolic COT increased when walking with the device active.**

I. INTRODUCTION

Recent research in rehabilitation and gait assisting devices has mostly been focused on the ankle joint during the period between heel-strike and push-off [1]–[7], due to the substantial amount of negative work at heel-strike and the large positive ankle work required at push-off [8], [9]. Previous studies by [10], [11] showed that muscles are less efficient in performing positive work than performing negative work. Studies have also shown the potential for reducing metabolic expenditure of subjects by decreasing muscle activation when performing positive work [1]–[4], [6], [7]. To assist muscle force production, an external mechanism must provide an assistive force in parallel to the associated muscle [12]. Most existing gait assistive devices require a power source which increases the total mass of the system, costing additional metabolic expenditure to the user [13], [14]. An effective gait assistive device requires an optimal balance between the assistive force provided and power consumption. As an example, a recent development of a portable device examined alternative methods of obtaining the assistive force by harnessing the energy dissipated at heel-strike and later returning the energy to help with ankle push-off [15].

In parallel, studies of human walking have shown that the energy required to propel oneself over a level ground is minimal, which classified human gait as a predominantly passive motion [16]. Recent research developed an individual limb method to investigate the contribution of the leading and trailing legs to the overall mechanical work during step-to-step transition [17]. This approach accounts for the mathematical cancellation of the positive and negative forces during multi-limb support [8], [18], and identified that the human gait requires more energy than previously estimated from a passive walking model. Derived from the compass gait model, a main energetic determinant of gait is the step-to-step transition period when the center of mass is redirected from the downward arc to the subsequent arc of the next step. As previously proposed by [17], [19], [20], a significant amount of metabolic expenditure is required to redirect the center of mass during this period. Based on this theory a new class of gait assisting devices should be developed to explore the possibility of reducing the cost associated with the step-to-step transition. We propose a new device that is entirely passive and capable of transferring energy from the leading leg to the trailing leg during step-to-step transition. The purpose of this study is to investigate the effects on the mechanical cost of transport (COT) and the metabolic expenditure when walking with the device. We hypothesize that walking with the device will reduce the mechanical cost during the step-to-step transition and subsequently the metabolic cost of walking.

II. METHODOLOGY

A. The Device

We developed a device that couples the lower limbs allowing energy transfer between legs during step-to-step transition. The device is composed of elastic elements and a cable connected in series and runs through a system of pulleys. The effective spring constant of the elastic elements is $\sim$81N/m. The elastic elements were chosen such that they were capable of providing 10% of the peak ankle moment that occurs during normal overground walking. The initial length of the cable and elastic elements were chosen based on the shortest subject such that no slack developed in the elastic cable and the elastics did not enter the pulleys during pre-swing. Total mass of the device, including the backpack frame is approximately 1kg. A hook clip is connected at the ends of the elastic

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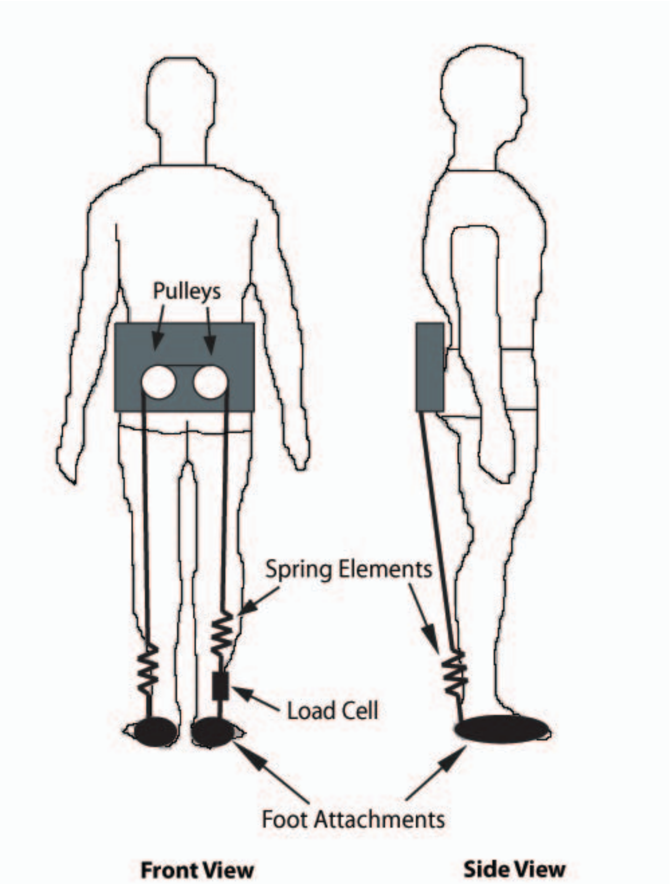

Fig. 1. A basic depiction of the inter-limb device as it would be located on a subject. The backpack frame onto which the device is mounted is not represented in this figure.

elements to provide easy donning and doffing with the pulley cable and foot attachments. The foot attachments used are a commercially available 5-point foot harness purchased from Nautilus Inc. A visual representation of the device is presented in Figure 1 below. As previously mentioned, the function of the device is to transfer energy from the leading leg to the trailing leg during step-to-step transition. Maximum deflection of the elastic elements occur during the redirection of the COM (heel-strike) and minimum deflection occurs during the swing phase.

B. *Subjects*

Five male subjects (age: 23.4 ± 2.7 yrs, mass: 70.97 ± 10.71 kg, height: 176.3 ± 6.0 cm, leg length: 91.82 ± 3.94 cm, femur length: 40.52 ± 2.03 cm, shank length: 41.38 ± 1.03 cm (mean ± S.D.)) were recruited to participate in this study. None of the subjects showed any sign of gait impairments and were without any known orthopaedic, neurological, or cardiovascular diseases. The subject mass was measured using a medical scale and the limb segment lengths were measured using a measuring tape. The subject's leg length is the distance between the floor and the greater trochanter while the subject stood in anatomical position. The subjects were asked to wear their own gym shoes over which the foot attachments were secured. All subjects gave their informed consent before participating in the study in accordance with the Queen's University Ethics board.

C. *Measurement*

The force profile from the elastic elements was measured using an ATI Nano25-E Transducer with custom aluminum mounts using eye bolts for easy attachment with the hook clips to the elastic elements and the foot attachments. The load cell was mounted in-series with the elastic elements and the data was collected through MATLAB-Simulink using a National Instruments DAQ board. The ground reaction forces were measured using the Tandem force treadmill system from AMTI. The data was synchronized in Qualisys Track Manager (QTM) using a single pulse synchronization signal sent from the NI-DAQ board to the QTM software. Both of the load cell and treadmill force data were collected at 600Hz. The breath by breath metabolic data was collected using the portable $K4b^2$ open-circuit respiratory unit by COSMED.

D. *Experimental Procedure*

All testing took place at the Human Mobility Performance Lab located in Hotel Dieu Hospital, Kingston, Ontario, Canada. The heel portion of the subject's shoes were taped with medical tape before attaching the foot harnesses to help maintain the proper position. Prior to testing, the subjects were given an acclimation period of $\sim 5mins$ on the treadmill at the desired walking speed of 1.2m/s with the device in active mode. The subject's resting metabolic rate (RMR) was measured during a 10min quiet sitting period in an isolated room. The subjects were asked to sit quietly in a room without physical, auditory or visual distractions. After measuring the resting metabolic rate, a 5s static calibration trial was collected with the subject in anatomical position on the Tandem treadmill. The subjects were asked to walk on the treadmill at a speed of 1.2m/s for 10mins under two conditions: 1) with the device in passive mode, without the elastics attached and 2) in active mode with the elastics attached, allowing energy transfer between the legs. During the passive trial condition, the elastics were detached from the subject's feet and secured on the backpack frame but none of the components were removed from the subject such that the effect of mass on the rate of metabolic energy expenditure is minimized. The subjects were instructed to walk naturally on the treadmill while maintaining fore-aft and medio-lateral position. When the subjects drifted on the treadmill they were instructed to correct their position as required such that proper contact was made with the embedded force platforms in the treadmill.

Metabolic data was collected over the entire 10min trial once the desire treadmill speed was reached, while the force data was collected during the last 5mins of the walking trials. The subjects were notified prior to starting or stopping the treadmill and an emergency stop was accessible to the subject had they felt unsafe or required an immediate stop. A minimum rest period of 3min was given to the subjects and they were offered water between trials. The order of the two trial conditions was randomized for each subject to minimize the effects of habituation.

III. ANALYSIS

All of the data was processed using a custom MATLAB script. The data is synchronized before analysis and the force data was filtered using a 2^{nd} order, zero-lag Butterworth with a cutoff frequency of 50Hz. The ground reaction force data is segmented into individual steps using a threshold of 10N. The cable force data was not analyzed in this study.

A. *Cost of Step-to-Step Transition*

The cost of step-to-step transition is calculated from COM velocity, power and work using the individual limb method as described in [17], [19], [20] and outlined herein.

1) Center of Mass Velocity: The velocity profile for the subject's center of mass (COM) is determined by integrating the ground reaction force (GRF) data.

$$\vec{v}_{com} = \int \frac{\vec{F}_{trail} + \vec{F}_{lead} - m \cdot \vec{g}}{m} dt + \begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} \quad (1)$$

where $\vec{F}_{trail}$ is the GRF vector of the trailing leg, $\vec{F}_{lead}$ is the GRF vector of the leading leg, $\vec{g}$ is the gravitational force vector [0; 0; $9.81 m/s^2$], *m* is the subject's mass and the last term is composed of the integration constant. The integration constant c_z is determined by assuming the average vertical velocity of the COM over a step is zero. Integration constants c_x is determined by assuming that the COM medio-lateral velocity at the end of the step is equal in magnitude but opposite in direction in relation to the velocity at the start of the step. c_y is determined by assuming the average velocity over the step is equal to the average overground walking speed.

2) Power and Work: The mechanical power and work are calculated as the dot product of the ground reaction force for each respective limb with the center of mass velocity previously determined.

$$P_{lead} = \vec{F}_{lead} \cdot \vec{v}_{com} \quad (2)$$

$$P_{trail} = \vec{F}_{trail} \cdot \vec{v}_{com} \quad (3)$$

The positive and negative mechanical work of the COM is the cumulative time-integral of the respective regions of positive and negative power.

$$W^{+} = \int_{POS} P_{trail} dt + \int_{POS} P_{lead} dt \quad (4)$$

$$W^{-} = \int_{NEG} P_{trail} dt + \int_{NEG} P_{lead} dt \quad (5)$$

The mechanical work performed by each leg during the step-to-step transition is averaged over 50 steps.

3) Step Length: Equation 6 summarizes the calculation for determining the subject's average step length. The average step length is calculated using the step period (T) and treadmill velocity. The step period is the time between heel-strike of each foot and is determined from onset of the vertical ground reaction force (10N threshold). Step frequency is the reciprocal of the step period and the step length is the product of the step frequency and treadmill velocity (V) or simplified as the product of the step period with treadmill velocity.

$$StepLength = V_{Treadmill} \cdot T \quad (6)$$

The mechanical COT of the leading and trailing leg is calculated by normalizing the mechanical work performed by each leg with the average step length (m) and the subject's body weight (N), [17].

B. *Metabolic Energy*

The rate of metabolic energy expenditure from the two conditions is analyzed using the following equation, [17], [21]:

$$P_{met,gross} = 16.58 (\frac{W \cdot s}{mlO_2}) \cdot \dot{\overline{V}}_{O_2} + 4.51 (\frac{W \cdot s}{mlCO_2}) \cdot \dot{\overline{V}}_{CO_2} \quad (7)$$

where $\dot{\overline{V}}_{O_2}$ and $\dot{\overline{V}}_{CO_2}$ are the measured rates of oxygen consumption and carbon dioxide production, respectively. The metabolic power for quiet sitting is subtracted from all of the treadmill walking trails to obtain the subject's net metabolic power (W). The metabolic rates are determined from one third of the metabolic data taken from the middle of the 10min trials to obtain steady-state data. The non-dimensional metabolic cost of transport (COT) is determined by normalizing the rate of metabolic expenditure to the subject's body weight (N) and treadmill speed (m/s). A two-tailed, paired Student t-test is conducted for step length, metabolic COT, and mechanical COT with a significant level of $p < 0.05$.

IV. RESULTS

Walking with the passive inter-limb device increased the subject's metabolic expenditure but decreased the mechanical work performed by the leading and trailing legs during step-to-step transition. Subject one had the smallest change in their rate of metabolic expenditure between the two walking conditions with a value of 6.86W, while subjects two to five had increases of 65.76W, 42.13W, 60.84W, and 83.02W, respectively.

The metabolic COT is presented in Figure 2 which also shows that subject one had the smallest increase in their cost of transport when walking with the device in active mode. Similarly, Figure 3 presents the mechanical COT for the trailing and leading leg during step-to-step transition.

Figure 4 illustrates the difference in step length, metabolic cost of transport, and mechanical cost of transport of the trailing and leading leg between the active and passive walking conditions. The Student t-test showed that using the device in active mode had a significant effect on the subject's step

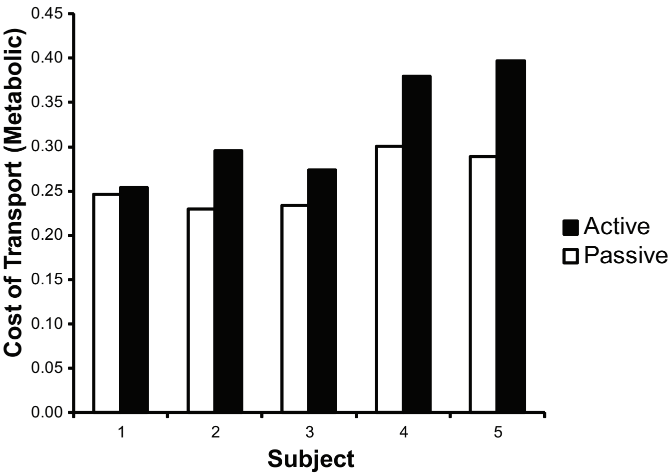

Fig. 2. The non-dimensional metabolic cost of transport for each subject while walking with the device in active and passive mode. Subject one has the smallest increase of 0.008 while subject five had the largest increase at 0.108.

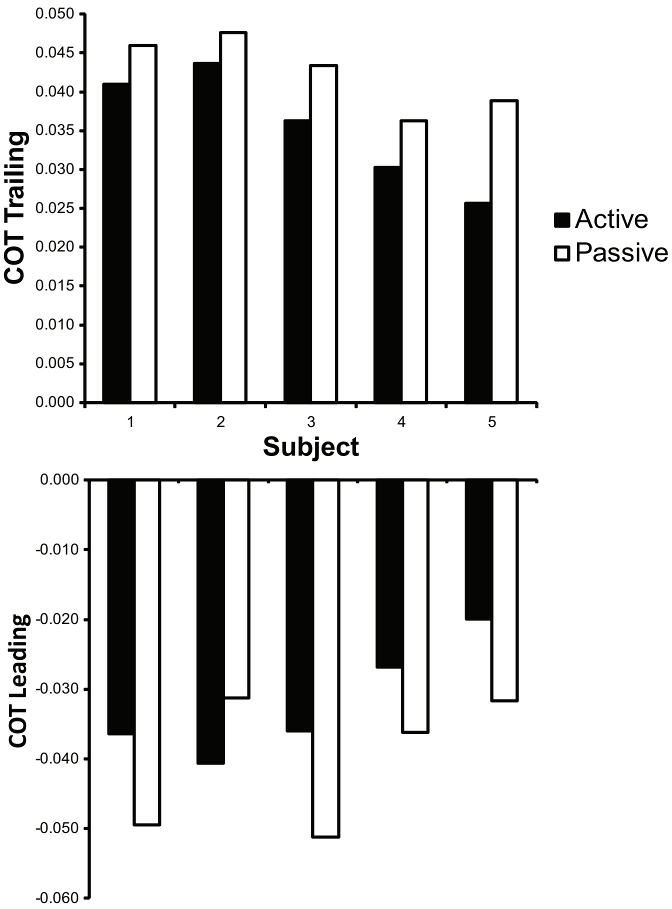

Fig. 3. The non-dimensional mechanical cost of transport for the leading and trailing leg for each subject while walking with the device in active and passive mode.

length, metabolic COT, and mechanical COT with the exception of the mechanical COT performed by the leading leg. The average step length of the subjects significantly decreased from 70.7cm to 68.9cm (p=0.017). The metabolic COT between the two walking conditions was also found to be significantly increased from 0.260 when walking with the device in passive mode to 0.320 when the device is in active mode (p=0.026). For the mechanical COT, the device significantly reduced the COT for the trailing leg from 0.042 in passive mode to 0.035 in active mode (p=0.012) but did not significantly reduce the COT of the leading leg from -0.040 in passive mode to -0.032 in active mode (p=0.146).

V. CONCLUSION AND DISCUSSION

Contrary to the step-to-step transition theory and our hypothesis, the metabolic COT did not change proportionally with the mechanical COT. The mechanical COT for the trailing leg significantly decreased while the leading limb did not. It is important to note that the mechanical cost of transport determined here is only over the step-to-step transition period and not for the overall gait cycle. The lack of significant difference between the active and passive conditions in the leading leg COT is attributed to the limited number of test subject and the results of Subject two. Since there are only five subjects, results from a single subject has a greater statistical impact. Comparing the trailing and leading COT between the subjects from Figure 3, the COT leading leg of Subject two is abnormally lower during the passive walking condition than any of the other four subjects. What's more interesting is the relative difference between the leading and trailing leg COT of each subject. Subject two has a much larger COT trailing leg than their COT leading leg (**1.5**) whereas the ratio between the COT leading and trailing leg of the remaining four subjects is closer to 1. A unity ratio is expected during steady state walking as the work done by the leading and trailing leg should be the same to maintain a steady walking speed. Any deviation away from unity indicates that the average walking speed is changing. This means that Subject two could have been increasing their walking speed during the passive walking condition and is confirmed by examining the force and motion data. By treating Subject two as an outlier and removing their data from the statistics, the p-value become 0.002 for the mechanical COT of the leading leg for the four remaining subjects. The change in mechanical COT of the trailing leg remains significant for the remaining four subject. Although the results show a significant change in the metabolic and mechanical COT, the current sample size is relatively small.

A potential contributor for the decrease in the mechanical COT is the change in the step length and step frequency. The use of the elastics on the device caused the subject to naturally decrease their step length (increase step frequency) while maintaining their walking speed on the treadmill. The correlation between the step length and mechanical COT observed in the current study does correspond with the step-to-step transition theory previous described in [19] where the mechanical COT during step-to-step transition decreases with a reduced step length and vice versa. Future experimentation will control for the subject's step frequency while walking

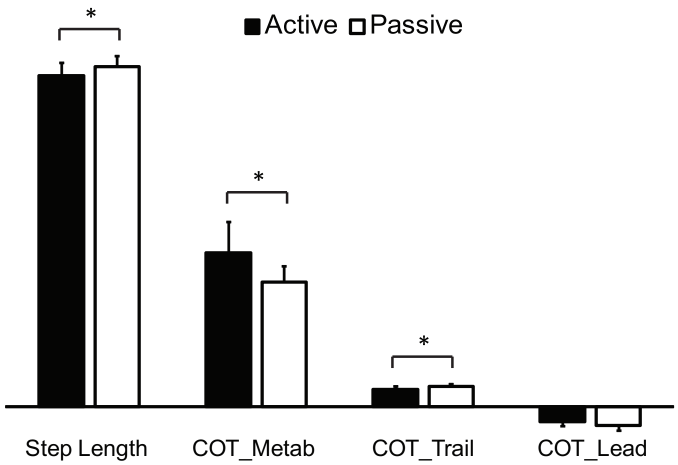

Fig. 4. Comparison of the step length, metabolic cost of transport, and mechanical cost of transport of the trailing and leading leg between the active and passive walking conditions.

with the device in active mode.

There are several factors which could result in the increase of the subject's metabolic COT such as: body composition, training effects, change in gait strategy and increase in positive work at the other lower limb joints during the remaining periods of gait. In comparison to the other subjects, Subject one was experienced who had at least 5hrs of previous walking experience with the device while the other four were naive to the device. The previous experience of Subject one may be a contributing factor in maintaining a similar metabolic expenditure between the two test conditions. The learning effect of devices implemented in walking has been shown to be significant by previous studies [22] and future research will investigate the effects of learning with the device on the subject's metabolic expenditure. Future research will also examine the changes in moments, work and power at the lower limb joints.

The body composition of each subject can also contribute to the variation in the observed differences in the metabolic COT. Subjects that were of similar height but lighter, had a relatively larger increase in their metabolic COT. This suggests that there may exist a subject specific spring constant and maximum spring deflection. In the current study, the device was configured to the shortest subject. This setup resulted in higher forces exerted on taller subjects. During the other periods of gait other than step-to-step transition, it is possible for the magnitude of joint work performed by the subject to shifted from performing negative work to into performing positive work due to the load caused by the elastic cable. Future studies will examine joint work to determine the effect of the elastic cable on gait. Another potential contributor to the increase in the rate of metabolic expenditure is the alteration in the subjects gait strategy as observed by the change in step length (and step frequency). From previous studies such as [23], a change in gait strategy such as step length and frequency could potentially contribute to the increase in metabolic cost as the subject deviates from their optimal combination of step length and frequency.

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