Preliminary Investigation of Effects of a Quasi-Passive Knee Exoskeleton on Gait Energetics

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***Abstract*— In this paper, we explain that the human knee behavior in the weight acceptance phase of gait (first *~40%* of gait cycle) resembles that of a linear torsional spring. This led us to study the effects of the assistance provided by a pair of quasi-passive knee exoskeletons, which implement springs in parallel with the knee joints in the weight acceptance phase. Using the exoskeletons in a series of experiments on seven participants, we found that the exoskeleton mildly but non-significantly reduces the metabolic power of walking. We also found that the metabolic power of walking is significantly correlated with both the positive rate of moment generation and positive mechanical power of the lower extremity joints. This suggests that augmenting exoskeletons can aim to reduce both the muscle force and work generation to reduce the metabolic cost of walking.**

***Index Terms*—Lower extremity exoskeleton, metabolic cost walking, energetics, variable-stiffness, knee biomechanics, quasi-passive mechanism**

I. Introduction

LOWER EXTREMITY augmenting exoskeletons emerged to improve the performance of humans via reduction of metabolic cost of walking, enhancement of load carrying capacity, reduction of fatigue, and improvement of posture [1]. Research on development of lower extremity exoskeletons led to substantial evolution in design techniques and control methods [2-6]. Researchers designed augmenting exoskeletons for the entire leg [2, 5, 7] and the hip [8], knee [9-11], and ankle [12] joints.

The common finding of previous exoskeleton research was that the exoskeletons were not able to reduce the metabolic cost of walking when compared with normal walking without exoskeletons [1, 13]. These observations led researchers to conduct basic research on the human physiology in interaction with exoskeletal systems [7, 9, 12, 14]. In order to expand upon this line of basic research, we developed a pair of quasi-passive knee exoskeletons to study human body physiology in interaction with exoskeletal impedances, as shown in Fig. 1 and detailed elsewhere [9].

Fig. 1. The quasi-passive exoskeleton implements a spring in parallel with the knee joint in the weight acceptance phase and allows free rotation throughout the rest of gait cycle.

The knee joint undergoes substantial loading in the weight acceptance phase of gait, which is the first 40% of the gait cycle, and remains relatively inactive during the rest as schematically shown in Fig. 2-top [15, 16]. The moment-angle behavior of lower extremity joints can be characterized by the concept of quasi-stiffness, which is defined the slope of a linear fit to the moment-angle data of the joints in a period of the gait cycle [16-19]. Previous research shows that the knee behaves similarly to a torsional linear spring in the weight acceptance phase at the preferred gait speed, which can be characterized by the knee quasi-stiffness (K_K) in this phase [15, 16]. This characteristic implies that a simple linear spring may be able to replace at least some component of the work completed by the knee at the initiation of the stance phase of gait.

To study the spring-type behavior of the human knee joint and investigate the motor adaptation in lower extremity joints, we designed and fabricated a pair of quasi-passive knee exoskeletons, as shown in Fig. 1 [9]. When worn on a user, each exoskeleton implements a spring in parallel with the knee joint in the weight acceptance phase and allows free rotation during the rest [9].

In this paper, we report the findings of a preliminary

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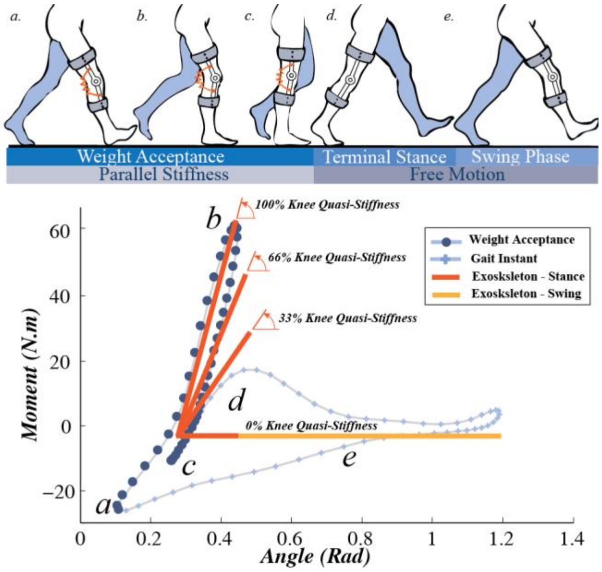

Fig. 2. Top: The exoskeleton implements a spring in the weight acceptance phase of the gait corresponding to the first *~40%* of the gait cycle. Bottom: The experimental conditions involved walking with the exoskeletons with four levels of stiffness including *0%, 33%, 66%,* and *100%* of the estimated knee quasi-stiffness.

investigation on the effects of the exoskeletons assistance on the energetics of gait in terms of the metabolic power of walking. We hypothesized that the metabolic power of walking is correlated with the rate of moment generation and mechanical work suggesting that a spring in parallel with the knee joint in the weight acceptance phase can fully/partially unload the knee joint and result in a reduction in the metabolic power of walking and therefore positively influence the energetics of gait. We tested this hypothesis using the exoskeletons in a series of experiments on seven participants during walking on a treadmill. We studied the average positive mechanical power and average positive rate of moment generation (as an indicator of the muscle force generation) as two determinants of the metabolic power [12, 20-24]. Previous research suggests that there might be an optimal level of assistance provided by an exoskeleton [7, 13], therefore this investigation included four levels of exoskeletal assistance/stiffness as: 0%, 33%, 66%, and 100% of the estimated anatomical knee quasi-stiffness.

II. Methods

A. Quasi-Passive Knee Exoskeleton

We used a pair of quasi-passive knee exoskeletons to study assistance by a parallel spring applied during the weight acceptance phase, as shown in Fig. 1. The design and function of the exoskeletons are detailed elsewhere [9]. Briefly, each exoskeleton implements an interchangeable spring in parallel with the knee joint in the weight acceptance phase of gait as schematically shown in Fig. 2-top.

B. Data Collection Instrumentation

Three dimensional motion data were collected using a motion capture system of ten cameras (Qualysis, Gothenberg, Sweden) and the Qualisys Track Manager software to track reflective markers which were placed on body landmarks according to convention described elsewhere [9, 25].

TABLE I
The Knee Quasi-Stiffness and Exoskeleton Stiffness Across Conditions

No.	Speed *(m/s)*	Measured K_K *(Nm/rad)*	Estimated K_K *(Nm/rad)*	33% K_E *(Nm/rad)*	66% K_E *(Nm/rad)*	100% K_E *(Nm/rad)*
1	1.12	156	240	81	160	239
2	1.39	257	267	89	174	239
3	1.34	318	393	128	239	328
4	1.43	258	274	92	174	239
5	1.21	117	247	81	160	239
6	1.21	149	235	81	160	239
7	1.03	110	235	81	160	239
Mean	**1.25**	**195**	**270**	**90**	**175**	**252**
SD	**0.15**	**82**	**56**	**17**	**29**	**34**

The exoskeletons controller wirelessly transferred the moment profiles of the left and right exoskeletons, which were synchronized with the data of the motion capture system. We analyzed the data from the motion capture system, instrumented treadmill, and the exoskeletons in Visual3D software (C-Motion, Gaithersburg, MD) and Matlab software (Mathworks, Natick, MA) to obtain the kinematic and kinetic profiles of the joints.

The rate of oxygen uptake ($\dot{V}O_2$, *mL/min*) was measured using a K4b^2 portable metabolic measurement system (COSMED, Rome, Italy). First, $\dot{V}O_2$ was measured for a 2-min standing trial as a baseline for each subject. For each walking trial, $\dot{V}O_2$ was measured during minutes 8-10 and were averaged over *20 secs* increments for the 2-min collection period. We ensured that the rate of oxygen uptake was steady for each trial. Net rate of oxygen uptake ($\dot{V}O_2'$) for each trial was calculated as the average value of $\dot{V}O_2$ during walking subtracted by the average $\dot{V}O_2$ of the standing trial.

C. Human Subjects and Experimental Conditions

Seven healthy adult volunteers with average height of *1.76±0.07 m* and mass of *77.6±12.7 kg* were recruited and written informed consent was obtained prior to participation. Table I lists the demographics of the volunteers. The experimental protocols were approved by Yale University Institutional Review Board, Human Use Review Committee of United States Army Research Institute of Environmental Medicine, Army Human Research Protections Office, and Battelle Institutional Review Board.

The participants walked on the treadmill wearing the exoskeleton with four levels of stiffness (K_E) including 0%, 33%, 66% and 100% of the anatomical knee joint quasi-stiffness, as schematically shown in Fig. 2. The quasi-stiffness of the knee joint in the weight acceptance phase was estimated as [16]:

$$K_E\left(\frac{N.m}{rad}\right) = \left(5.21\sqrt{H^3} - 7.5\sqrt{H} - 5.83H + 11.64\right)M - 6 \quad (1)$$

Here, H *(m)* is the height and M *(kg)* is the mass of the participant. The values of measured (real) and estimated subject's quasi-stiffness, and the exoskeleton stiffness values are listed in Table I. The measured quasi-stiffness of the knee joint was obtained through inverse dynamics analysis, as outlined elsewhere [16].

The study included three sessions with one to two days of rest between each session. The sessions included two orientation sessions followed by a data collection session including *8-10 mins* of walking for each trial, as detailed elsewhere [9]. We measured the mass and height of the volunteers on the first visit and inserted them in equation (1) to obtain estimated values for the knee-quasi-stiffnesses of each participant. As reported in Table I for the exoskeleton spring, we used commercial springs with stiffness values closest to 33%, 66%, and 100% of the estimated knee quasi-stiffness in the corresponding experimental conditions.

D. Calculation of Mechanical and Metabolic Power

Average Metabolic Power: The rate of oxygen uptake was used to calculate the average metabolic power as [26]:

$$P_{met}\left(\frac{W}{kg}\right) = 21\,\dot{V}O_2'/M \quad (2)$$

Average Positive Power: Visual3D software was used to calculate the power profiles for each trial through an inverse dynamic analysis, as detailed elsewhere [9]. The power profiles were normalized using the mass of the participant.

For each trial, four consecutive gait cycles were identified by the right heel strike and confirmed to have complete force plate signals and complete marker data for all subjects [13]. The profiles of the four gait cycles were averaged to obtain intra-subject mean profiles. The intra-subject mean power profiles of the left and right sides were averaged and used to obtain the inter-subject mean and standard deviation of positive average power.

For each gait cycle, the average positive power of each lower extremity joint and exoskeleton (i = {H: Hip, K: Knee, and A: Ankle}) was calculated as [12]:

$$\bar{P}_i^+\left(\frac{W}{kg}\right) = \frac{W_i^+}{T} \quad (3)$$

where, $T\,\langle sec\rangle$ is the duration of the gait cycle and (W_i^+) is the positive mechanical work that was calculated using the following equation:

$$W_i^+\left(\frac{J}{kg}\right) = \int P_i^+(t)\,dt \quad (4)$$

Here, $P_i^+\left(\frac{W}{kg}\right)$ is:

$$P_i^+(t) = \begin{cases} P_i(t) & if\ P_i(t) > 0 \\ 0 & if\ P_i(t) \le 0 \end{cases} \quad (5)$$

where $P_i(t)$ is the power in the sagittal plane at instant t. The average positive mechanical power ($\bar{P}_{mech}^+$) was calculated as the summation of the positive power of the hip, knee, and ankle joints.

Average Rate of Positive Moment Generation: Visual3D software and Matlab were used to conduct inverse dynamics analysis and extract the intra-subject moment profiles of the participant similarly to calculation of the mechanical power, as detailed elsewhere [9]. Average positive rate of moment generation of the knee joint ($\bar{\dot{M}}_K^+$) was calculated as:

$$\bar{\dot{M}}_K^+\left(\frac{Nm}{kg.s}\right) = \int \dot{M}_K^+(t)\,dt\,/\,T \quad (6)$$

where:

$$\dot{M}_K^+(t) = \begin{cases} \frac{dM_K}{dt} & if\ \frac{dM_K}{dt} > 0 \\ 0 & if\ \frac{dM_K}{dt} \le 0 \end{cases} \quad (7)$$

where, $M_K(t)$ is the moment of the knee joint in the sagittal plane at instant *t*.

The means and standard deviations (SD) of $\bar{\dot{M}}_K^+$, $\bar{P}_{mech}^+$, and P_{met} were calculated and shown across the conditions in Fig. 3. The effects of exoskeleton assistance on $\bar{\dot{M}}_K^+$, $\bar{P}_{mech}^+$, and P_{met} were investigated using one-way ANOVA across the conditions as well as a post hoc t-test with Bonferroni correction that resulted in a *p-value* of *0.008*. Additionally, we individually compared the conditions 33%, 66%, and 100% with the condition 0% using one-way ANOVA with *p-value* of *0.05*. To inspect potential effects of moment generation rate and mechanical work, we plotted P_{met} with respect to $\bar{\dot{M}}_K^+$ and $\bar{P}_{mech}^+$, and applied linear regression for each trial.

III. Results

Fig. 3 shows the mean ± 1 SD values of $\bar{\dot{M}}_K^+$, $\bar{P}_{mech}^+$, and P_{met} across the conditions. The exoskeleton assistance resulted in a mild non-significant reduction in $\bar{\dot{M}}_K^+$ from 0% to 33% and from 66% to 100%. We observed that the exoskeleton assistance did not affect $\bar{P}_{mech}^+$. Comparing 0% and 100% conditions, the exoskeleton assistance non-significantly reduced P_{met} by *5%*.

Fig. 4 includes the graphs of P_{met} with respect to $\bar{\dot{M}}_K^+$ and $\bar{P}_{mech}^+$ as well as first order polynomials fitted to the data of the conditions that included the exoskeletons. The coefficients of the polynomials are significantly different than zero ($p <$ *0.05*) indicating that P_{met} has significant correlations with both $\bar{\dot{M}}_K^+$ (R^2=*33%*) and $\bar{P}_{mech}^+$ (R^2=*15%*), with higher R^2 value for the correlation with $\bar{\dot{M}}_K^+$.

IV. Conclusions and Discussion

This paper reports the effects of the assistance provided by a pair of quasi-passive knee exoskeletons on the energetics of walking. Each exoskeleton implemented springs with four levels of stiffness, which were roughly equal to *0%, 33%, 66%* and *100%* of the knee quasi-stiffness, in parallel with the knee joint during the stance phase. We found that the exoskeleton assistance mildly but non-significantly reduced the metabolic power of walking.

We considered the average positive rate of moment generation (as an indicator of force generation of the muscles) and positive power as two determinants of the metabolic cost of walking, as suggested by others [12, 20-24]. We found that the metabolic power is significantly but mildly correlated with both positive rate of moment generation and positive mechanical power, suggesting that the exoskeleton reduced the rate of metabolic consumption via unloading the muscles that stabilize the knee joint. This finding is in agreement with findings of research regarding exoskeletal augmentation of the ankle during gait [12, 24].

Considering that the knee joint generates negligible mechanical work during the weight acceptance phase, the findings of this research suggest that reducing the rate of moment generation can be a viable method in the design of augmenting exoskeletons to reduce the metabolic power of walking.

As future research, we intend to investigate the energetics of gait in more details to include the effects of the exoskeleton

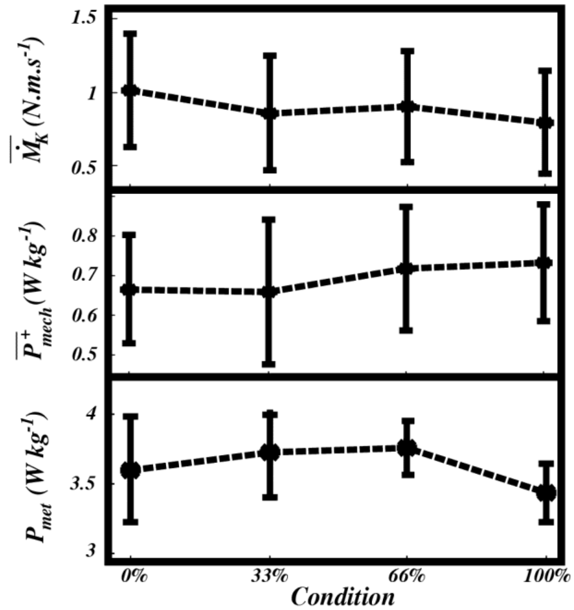

Fig. 3. Top: Average positive rate of moment generation for the knee joint, Middle: Average positive mechanical power of the knee, and Bottom: Metabolic power of walking across the experimental conditions. The error bars indicate ±1 SD around the inter-subject mean values. The solid lines indicated the significant changes between the conditions.

mass and kinematic constraints imposed by the exoskeleton articulations. We will study the effects of exoskeleton impedance on the work and moment generation of all lower extremity joints. We also intend to study the EMG activities of the muscles in response to exoskeleton impedance.

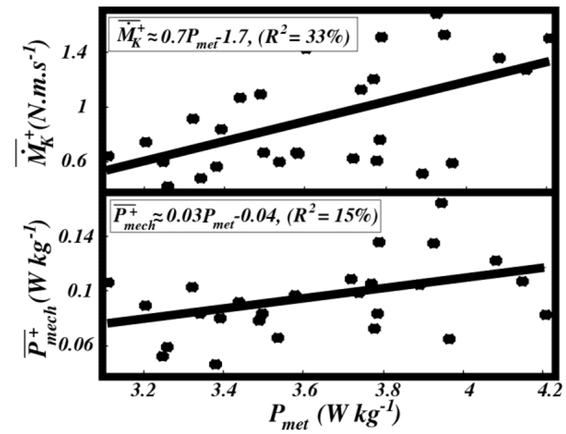

Fig. 4. Average positive rate of moment generation (top) and average positive power (bottom) with respect to the metabolic power. The graphs also include linear fits that show significant correlation ($p<0.01$ for the coefficients of the fit) between the parameters.

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