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Effects of Exoskeletal Stiffness in Parallel with the Knee on the Motion of the Human Body Center of Mass during Walking

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***Abstract*— In this paper we investigate effects of the mass, kinematic constraints imposed by the joint, and assistance provided by the spring of a pair of quasi-passive knee exoskeletons on the motion of the human body center of mass during normal walking. The exoskeletons implement a spring in parallel with the knee joint in the weight acceptance phase of gait, and allow free rotation during all other phases. We begin with a brief explanation of the exoskeleton design, which employs a friction-based latching mechanism to engage/disengage a spring in parallel with the knee. Additionally, a pair of joint-less mass replicas of the exoskeletons were used to separately investigate the effects of the exoskeleton added mass and articulation. It was found that the exoskeleton mass is the main contributor to the changes in the motion of the center of mass, with more pronounced fluctuations of the center of mass in the mediolateral direction, while the exoskeleton joint and spring had negligible effects over and above those of the mass. Additionally, the exoskeleton mass and assistance conditions respectively resulted in a non-significant increase and a non-significant decrease in the total mechanical work of the body.**

***Index Terms*—Lower extremity exoskeleton, Center of Mass, variable-stiffness, knee biomechanics, quasi-passive mechanism**

I. INTRODUCTION

Understanding the performance of the human body during interaction with engineered systems is insightful to several disciplines including orthotics [1], bipedal robot modeling and design [2], rehabilitation and physical therapy [3], and fundamental physiology and biomechanics. In order to gain insight into this interaction, researchers have used exoskeletal systems to study the human motor adaptation to external perturbations/assistance to the lower extremities [4-6].

To date, these studies have mostly focused on the adaptation of lower extremity movement patterns to external assistance/perturbation, performance augmentation using exoskeletal assistance [4, 6-8], and evaluating the effects of local assistance to a joint on the global movement of the human body center of mass (COM) [9]. The motion of the COM is a fundamental parameter in biomechanical analysis and characterization of gait [10, 11]. It relates to the overall motion of the human body, estimates energy changes, mechanical work, and gait efficiency, and describes gait symmetry, balance and stability [11-14].

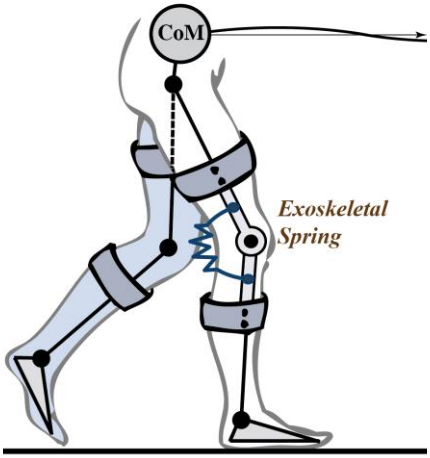

Fig. 1. The quasi-passive exoskeletons engage springs in parallel with the left and right knee joints in the weight acceptance phase and disengage them during the rest of gait. We investigate the effects of the exoskeletons on the motion of the human body center of mass

Characterization of the effects of exoskeletal assistance, locally provided to a lower extremity joint, on the motion patterns of the COM is informative to: a. evaluate the overall energetic performance of human body in interaction with exoskeletons, b. understand the biomechanical contribution of lower extremity joints to the overall motion and energy of the COM, c. identify if the exoskeleton perturbs gait stability and symmetry, and d. evaluate the overall performance the exoskeletons. In this paper, we follow a similar line of research and evaluate the effects of a spring in parallel with the knee joint on the motion of the COM, as schematically shown in Fig. 1.

Among lower extremity joints, the knee joint demonstrates several major functions in walking, including supporting the weight of the body in the stance phase and flexing in the swing phase to enable foot clearance and obstacle avoidance [15, 16]. The knee joint experiences three consecutive phases in a gait cycle, as schematically shown in Fig. 2. The main loading phase of the knee is the weight acceptance phase (first *~40%*, as depicted in Fig. 2 points *a* to *c*) where the knee exhibits an arc of flexion. The knee flexion in the weight acceptance phase was initially hypothesized to be a determinant of minimizing the vertical travel of the COM

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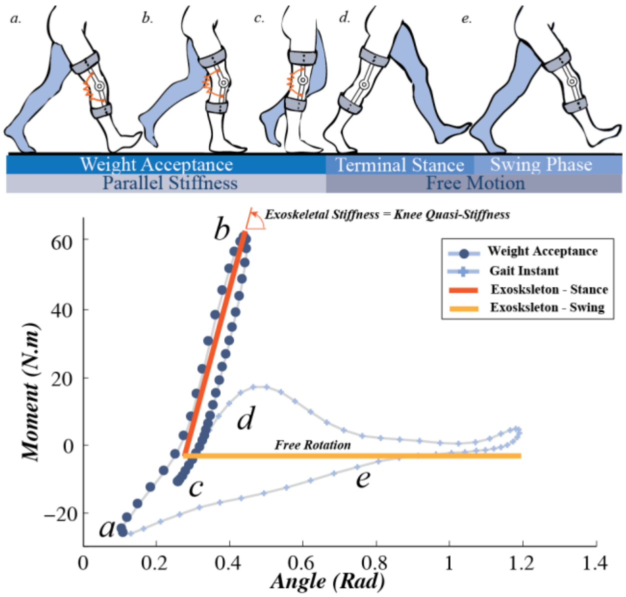

Fig. 2. Top: Schematic view of performance of the knee exoskeleton. Bottom: Moment-angle behavior of the knee joint. The human knee behaves similarly to a linear torsional spring in the weight acceptance phase inspiring the design of the semi-passive knee exoskeleton. The stiffness of the exoskeleton was chosen to be equal to the knee quasi-stiffness in the weight acceptance phase of gait.

[17], but later was shown to function as a shock absorption mechanism [16, 18, 19].

The concept of quasi-stiffness is used to explain the overall behavior of the lower extremity joints in the linear loading phases of gait [20-24]. The quasi-stiffness is defined as the slope of a line fitted to the moment-angle graph of a lower extremity joint in a phase of the gait and primarily explains the overall moment-angle behavior of the joint [22, 23, 25]. Previous research shows that the knee behaves close to a linear torsional spring at the preferred gait speed in walking [15, 16], leading researchers to develop quasi-passive exoskeletons that implement a spring in parallel with the knee to assist this joint in the stance phase [8, 26, 27].

In this paper, we investigate the effects a quasi-passive knee exoskeleton on the motion patterns of the COM. More particularly, we examined variations in travel and velocity of the COM as a result of the exoskeleton mass, kinematic constraints imposed by the exoskeleton joint, and assistance by the exoskeleton. We hypothesized that *an exoskeletal spring in parallel with the knee joint in the stance phase would not perturb the motion of the COM*. To test this hypothesis, we used a pair of similar quasi-passive knee exoskeletons that implemented springs in parallel with the right and left knee joints in the weight acceptance phase of gait and allow free rotation during the rest. Each exoskeleton spring stiffness is approximately equal to the natural knee quasi-stiffness in the weight acceptance phase of walking on level ground [15, 16]. We additionally used a pair of joint-less replicas of the exoskeletons to investigate the effect of exoskeleton mass and joint on the motion of the COM. Fig. 3 shows the exoskeletons on the top and the mass replicas on the bottom. Using the mass replicas and exoskeletons across four conditions allowed us to separately investigate the effects of mass, joint, and stiffness of the exoskeletons on the motion of the COM.

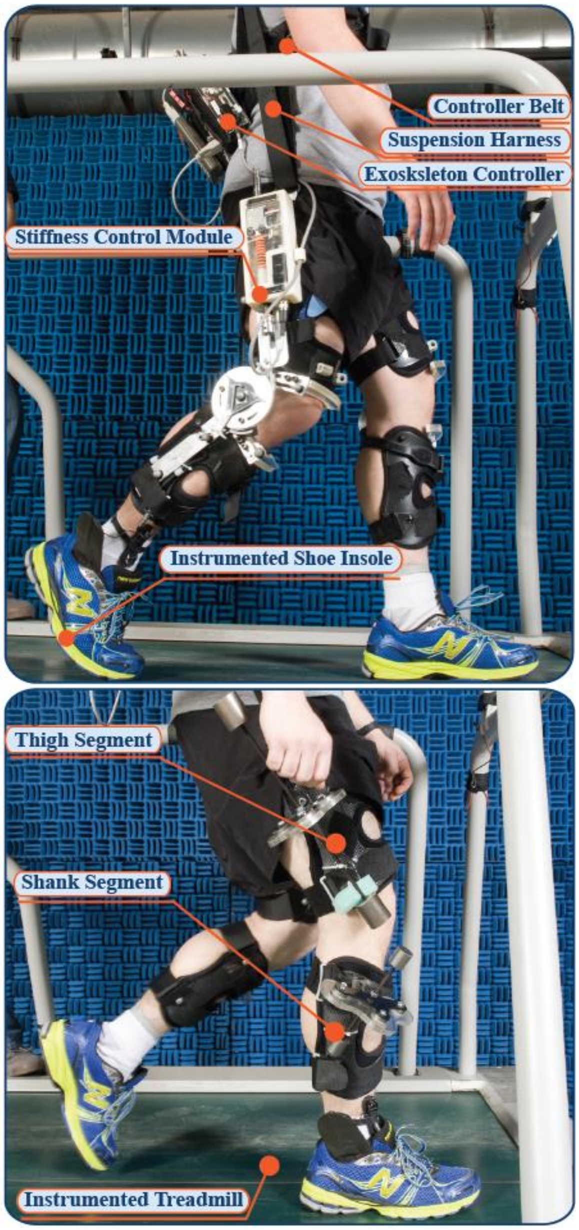

Fig. 3. Top: Quasi-passive knee exoskeletons worn on one of the participants during walking on an instrumented treadmill. Bottom: Joint-less mass replicas of the exoskeletons worn on a participant.

II. EXPERIMENTAL HARDWARE

A. *Quasi-Passive Knee Exoskeleton*

Each of the exoskeletons employs a quasi-passive mechanism to engage a spring in parallel with the knee joint in the weight acceptance phase of gait and disengage it during the rest. Each of the exoskeletons is composed of an adjustable uniaxial (i.e. simple hinge) knee brace, a stiffness control module (SCM), and a pulley. The SCM is mounted on the thigh cuff of the exoskeleton brace and the pulley on the shank cuff of the exoskeleton. The SCM shaft is attached to the pulley with a steel tendon and slides inside the SCM along with the rotation of the pulley.

To engage/disengage the assistance spring, the SCM utilizes

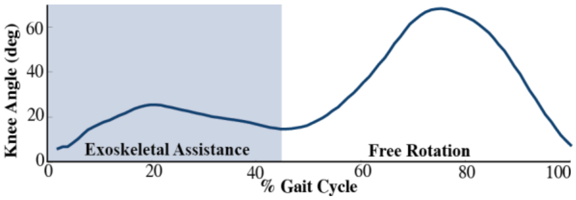

Fig. 4. Knee angle profiles and the period where the exoskeleton spring is engaged

TABLE I
MODEL MASS PROPERTIES OF THE EXOSKELETON AND MASS REPLICAS

Side	Segment	Weight (kg)	I_{xx} ($kg.m^2$)	I_{yy} ($kg.m^2$)	I_{zz} ($kg.m^2$)
Right	Thigh	1.68	0.02370	0.02312	0.00211
	Shank	0.77	0.00217	0.00249	0.00122
Left	Thigh	1.81	0.02370	0.02312	0.00211
	Shank	0.82	0.00217	0.00249	0.00122

Measured Weights:
Left Exoskeleton Weight = *2.63 kg*
Right Exoskeleton Weight = *2.45 kg*
Controller Unit Weight = *2.4 kg*
Total Weight = *7.48 kg*

TABLE II
DEMOGRAPHIC DATA OF THE PARTICIPANTS AS WELL AS THE STIFFNESS OF THE EXOSKELETON SPRING

No.	**Gender**	**Age**	**Height (m)**	**Weight (kg)**	**Preferred Gait Speed ($^m/_s$)**	**Measured Knee Quasi-Stiffness ($^{Nm}/_{rad}$)**	**Estimated Knee Quasi-Stiffness ($^{Nm}/_{rad}$)**	**Exoskeleton Stiffness ($^{Nm}/_{rad}$)**
1	F	24	1.70	79.9	1.43	258	274	239
2	M	24	1.69	78.5	1.39	257	267	239
3	M	26	1.83	68.0	1.21	117	247	239
4	M	23	1.68	71.0	1.12	156	240	239
5	M	29	1.77	66.7	1.21	149	235	239
6	M	22	1.76	67.0	1.03	110	235	239
7	M	21	1.89	103.8	1.34	318	393	328
8	M	22	1.73	86.0	1.30	321	299	328
	Mean	**23.9**	**1.76**	**77.6**	**1.25**	**211**	**274**	**261**
	SD	**2.6**	**0.07**	**12.7**	**0.14**	**88**	**53**	**41**

a friction-based latching mechanism as explained elsewhere [8, 28]. The exoskeleton controller engages the assistance spring when the heel contacts the ground and disengages it when the heel leaves the ground but the toe is on the ground, as shown in Fig. 4. The status of heel and toe contact with the ground is identified using an instrumented shoe insole, as explained elsewhere [8].

B. *Exoskeleton Mass Replica*

A pair of joint-less mass replicas of the exoskeletons was fabricated with mass, center of mass, and moment of inertia similar to those of the exoskeletons; except, they did not have orthotic joints connecting the thigh and shank cuffs, as shown in Fig. 3-bottom. The replicas were primarily composed of a thigh and a shank component each of which consisted of five steel cylinders mounted on brace cuffs that were similar to those of the exoskeletons. Mass properties of the exoskeletons and replicas are reported in Table I. The mass replicas and exoskeleton used similar cuffs, which were positions on the participants' leg in a similar way using surgical markers.

C. *Data Collection Instrumentation*

The experimental conditions included walking on an instrumented treadmill (AMTI, Watertown, MA). The treadmill comprises two synchronized treadmill belts positioned side-by-side, each on a separate force platform with a gap smaller than *1 cm*. A motion capture system of ten cameras (Qualysis, Gothenberg, Sweden) and the Qualisys Track Manager Software were used to record three dimensional motion data of the volunteers walking on the treadmill at a frequency of *240 frames/sec*. The exoskeleton simultaneously transferred data of the right and left knee angles, heel and toe sensors status, and feedback signal from the exoskeleton as indicators of the status of the engagement of the high-stiffness spring through the serial port using a wireless serial to Bluetooth adapter (from Willies Computer Software Co.) to a host computer that records the data using a LabView module. The exoskeleton also sent a synchronization signal to the Qualisys camera system that allowed us to synchronize the data from the exoskeleton with the data from the motion capture system and the force plates. Kinematic and kinetic profiles of the joints were calculated using Visual3D software (C-Motion, Gaithersburg, MD). The rest of analyses were done in Matlab software (Mathworks, Natick, MA).

III. METHODS

A. *Human Subjects and Experimental Conditions*

Eight healthy adult volunteers were recruited from the US Army Soldiers assigned to Headquarters, Research, and Development Detachment of Natick Soldier System Center. Inclusion criteria were a body height between *1.50* and *1.85 m* and a body weight less than *130 kg* according to the size limitations of the exoskeleton. Table II lists the demographics of the volunteers.

Written informed consent was obtained from each volunteer enrolled in the study prior to participation in the study. The study protocol was 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 in accordance with DoD 3216.02, protection of human subjects.

The experiments included the following four experimental conditions of treadmill walking:

1. Control Condition (CTRL): Without wearing the exoskeletons or mass replicas
2. Exoskeleton Mass (MASS): Wearing the joint-less mass replicas
3. Exoskeleton Joint (JOINT): Wearing the exoskeleton unpowered with exoskeleton steel tendon detached
4. Exoskeleton Spring (SPRING): Wearing the exoskeleton

with assistance spring stiffness (K_E) approximately equivalent the estimated quasi-stiffness of the anatomical knee in normal walking at preferred gait speed. The experiments included two additional conditions in which the exoskeleton spring stiffness was $^{1}/_{3}$ and $^{2}/_{3}$ of the knee quasi-stiffness. We decided to only report the condition where the exoskeleton stiffness is equal to the knee quasi-stiffness because we did not observe any noticeable effect as a result of the exoskeleton stiffness on the motion of the COM. The exoskeleton stiffness was sized using the following statistical model to estimate knee quasi-stiffness in the weight acceptance phase of gait based on the subject's body size [15]:

$$K_E = \left(5.21\sqrt{H^3} - 7.5\sqrt{H} - 5.83H + 11.64\right)W - 6 \qquad (1)$$

Here, *W (kg)* is the weight and *H (m)* is the height of the exoskeleton user. This statistical model showed a *9%* estimation error for subjects with weight from *67.7 kg* to *94.0 kg* and height from *1.43 m* to *1.86 m*. The values of gait speed, the estimated subject's quasi-stiffness, and the exoskeleton stiffness are listed in Table II. The measured quasi-stiffness was obtained from applying inverse dynamics to the kinematic and kinetic data collected during the experiments.

B. *Experimental Protocol*

The study included two orientation and one data collection sessions each taking place on one day with one to two day(s) in between for rest. The volunteers wore t-shirts, socks, and their own athletic shoes on all sessions. One the first visit, volunteers' weight and height were measured and used in equation (1) to estimate each volunteer's knee quasi-stiffness (K_K) and size the assistance spring stiffness of the exoskeletons.

Orientation Sessions: Two orientation sessions were included prior to the data collection session to allow the volunteers to become familiar with walking while wearing the exoskeletons. On the first visit, practice conditions included treadmill walk for *3 mins* at *4.83 km/h* to familiarize with treadmill walking followed by a 3-5 min seated rest. The second condition consisted in a treadmill walk to determine the subject preferred speed, starting from a zero-speed state up to a self-selected comfortable pace. This pace was then used as the preferred gait speed throughout the following practice and experimental treadmill walking conditions.

The exoskeleton was then fitted on the volunteers while seated, requiring the alignment of the exoskeleton joint with the anatomical knee joint. Vertical migration of the exoskeleton was minimized using suspension harness straps that were also put on the volunteer and fastened to the controller belt, which was strapped around the chest and shoulders. The study volunteers were asked to walk overground wearing the exoskeleton for each of the experimental conditions with the exception of the control condition. Overground walking consisted of about *640 m* at their own pace, which is approximately equivalent to the distance covered in *8 mins* of treadmill walking. An 8-min. treadmill walking at their preferred pace followed each overground walking condition after a 5-min seated rest. The order of the conditions for the first session was the same for all the subjects.

The second orientation session included only 10-min treadmill walking trials. The order of the all the six conditions was randomized for each volunteer. The order of the conditions during this session was the same as the order followed during the data collection session (last visit) for each of the volunteers.

Data Collection Sessions: Reflective markers were placed on body landmarks according to convention described elsewhere [29], with slight differences in that four-marker clusters were placed on the shank and the thigh such that the exoskeleton cuffs could fit on the limbs without blocking their visibility from the cameras. Additionally, a four-marker cluster was placed on the chest to track the trunk and pelvis as a single segment. Within each trial, a 30-second long data recording was taken after *4 mins* from the start of the trial.

C. *Calculation of Motion of the Human Body Center of Mass*

Visual3D software was used to calculate the acceleration of the COM in the sagittal, frontal, and horizontal (i.e. transverse) planes from the corresponding ground reaction forces. To obtain the motion of the COM, the Visual3D model of the limbs was used, which included the mass of the replicas for the MASS condition and the exoskeletons for the JOINT and SPRING conditions. The velocity and travel profiles of the COM were then calculated as the first and second time-integral of the acceleration profile. The motion (travel and velocity) profiles of the COM were normalized with respect to the body height. The remaining analysis was carried out in Matlab.

Four consecutive gait cycles, which were identified by the right heel strike, were identified for each trial and confirmed to have complete force plate signals and complete marker data for all subjects [30]. Intra-subject means were calculated by averaging the four gait cycles of each trial and the inter-subject mean and standard deviation (SD) of COM motion profiles were obtained from the corresponding intra-subject mean profiles. The inter-subject mean travel profiles of the COM along the vertical, mediolateral, and anteroposterior axes are plotted in Fig. 5. Using the mean and SD profiles, the coefficient of variability (CV; described elsewhere [31]) was calculated for each profile. Additionally, travel and velocity trajectories of the COM were plotted for the sagittal, frontal, and horizontal planes in Fig. 6 and 7.

To evaluate the effect of exoskeleton mass on the motion of the COM, we compared the motion profiles of the MASS and CTRL condition. In a similar fashion, the effect of the exoskeleton joint was evaluated by comparing the profiles of JOINT and MASS condition, and the effect of exoskeleton assistance by comparing the profiles of the SPRING and JOINT condition. To compare the motion profiles, we performed paired t-test between all 100 points of the aforementioned pairs of profiles, which was also verified by false discovery rate control as explained elsewhere [32]. To additional compare the profile temporal patterns, the COM motion profiles of the conditions (similar pairs of conditions used for the t-test) were also compared using linear regression

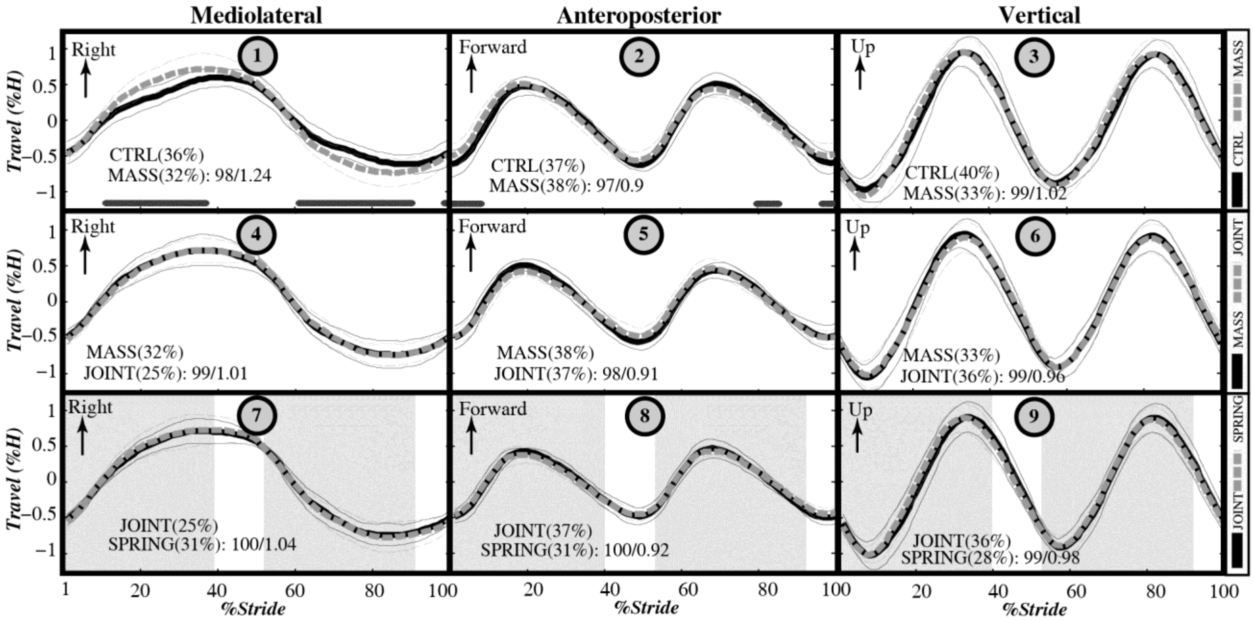

Fig. 5. Inter-subject mean profile of the travel of the body center of mass in mediolateral (left column), anteroposterior (middle column), and vertical (right column) direction. The first to third rows respectively include the profiles of the CTRL and MASS conditions, MASS and JOINT conditions, and JOINT and SPRING conditions. The stripe on the bottom of top left and top middle graph shows the period where the two profiles are significantly different. No other pair-wise comparison of profiles shows statistical differences. The shaded area in the third row shows the period where the exoskeleton spring was engaged

between the inter-subject mean profiles, as explained elsewhere [33]. The R^2 value of the regression indicates the degree of similarity of the patterns, while the slope refers to the scaling factor. For example, regression of two similar profiles gives a R^2 and a scale of 1; whereas, a down scaled profile (i.e. smaller range of values) with identical pattern would have $R^2=1$ and slope < 1. One should note that the scale is not very meaningful when R^2 is relatively low.

D. *Calculation of Total Mechanical Work*

Potential energy of the body was calculated as [10]:

$$P = Mg(D_Z - D_{Z,min})$$

where, M (kg) is the body mass, g is acceleration due to gravity, D_Z (m) is the vertical travel of the COM, $D_{Z,min}$ (m) is the lowest level of the COM. Kinetic energy was calculated as [10]:

$$K = M({V_X}^2 + {V_Y}^2 + {V_Z}^2)/2$$

where, V_X (m/s), V_Y (m/s), and V_Z (m/s) are respectively the mediolateral, anteroposterior, and vertical velocities of the COM. Total mechanical work was calculated as the differential of the total energy as Δ(P+K) and the work was calculated as [10]:

$$Work = \int |\Delta(\mathrm{P} + \mathrm{K})| dt$$

The total work per unit mass and distance, which is a metric for mechanical efficiency of gait, was calculated by dividing the total work by the body mass and the distance that the treadmill belt navigated. The total mechanical work is reported in Fig. 8.

IV. RESULTS

Fig. 5 includes the inter-subject mean COM travel profiles against percentage of stride. Fig. 6 and 7 include inter-subject mean trajectories of the travel and velocity of the COM in the sagittal, frontal, and horizontal planes. The first row to third rows of Fig. 5 to 7 respectively include data of CTRL and MASS, MASS and JOINT, and JOINT and SPRING conditions. The first row shows the effects of the exoskeleton mass, second row the effects of the exoskeleton joint, and the third row the effects of the exoskeleton spring on the motion of the COM. The values of R^2 of Fig. 5 range between 97% to 100% for the travel of COM for all four conditions implying that overall the motion patterns of the COM remained invariant under the effect of the exoskeleton mass, joint, and spring.

Effect of Mass: Graph 1 of Fig. 5 reports that regression Slope = 1.24 implying that the travel of the COM has increased along the mediolateral direction. The t-test results show that this increase is especially pronounced during the weight acceptance phases of both the left (60% to 90% of the gait cycle) and right (10% to 40% of the gait cycle) legs. Graph 2 of Fig. 5 reports a Slope of 0.9 for the travel of the COM suggesting that the travel range of the COM has decreased along the anteroposterior direction. The t-test results show that this decrease is significant at both the beginning and end of the gait cycle. Graph 3 of Fig. 5 show that the exoskeleton mass does not have any significant and noticeable effect of the vertical travel of the COM.

Graphs 2 and 3 of Fig. 6 and 7 show that the travel and velocity of the COM have been laterally stretched implying that the exoskeleton mass amplifies the mediolateral reciprocatory motion of the COM. Slight deformation is also seen in the COM velocity trajectories in the sagittal plane, as shown in graph 1 of Fig. 7. Fig. 8 also shows that the exoskeleton mass resulted in slight increases in the total mechanical work and mechanical efficiency, which were non-significant.

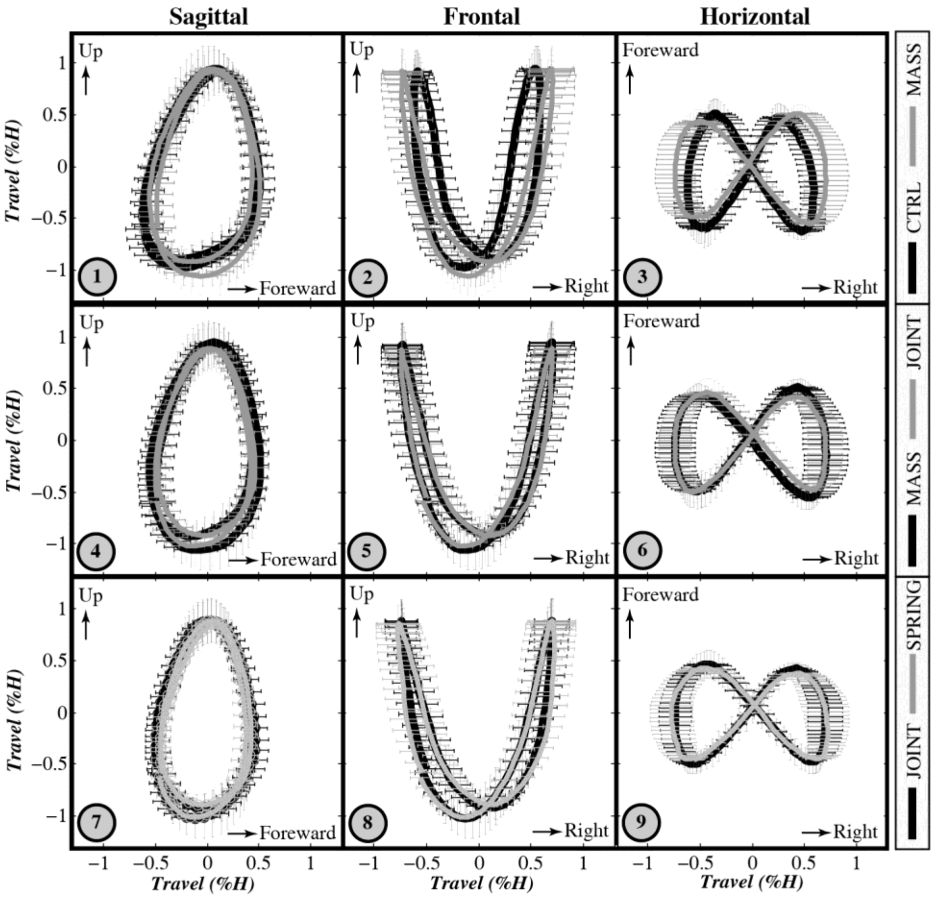

Fig. 6. Inter-subject mean trajectory of the body center of mass

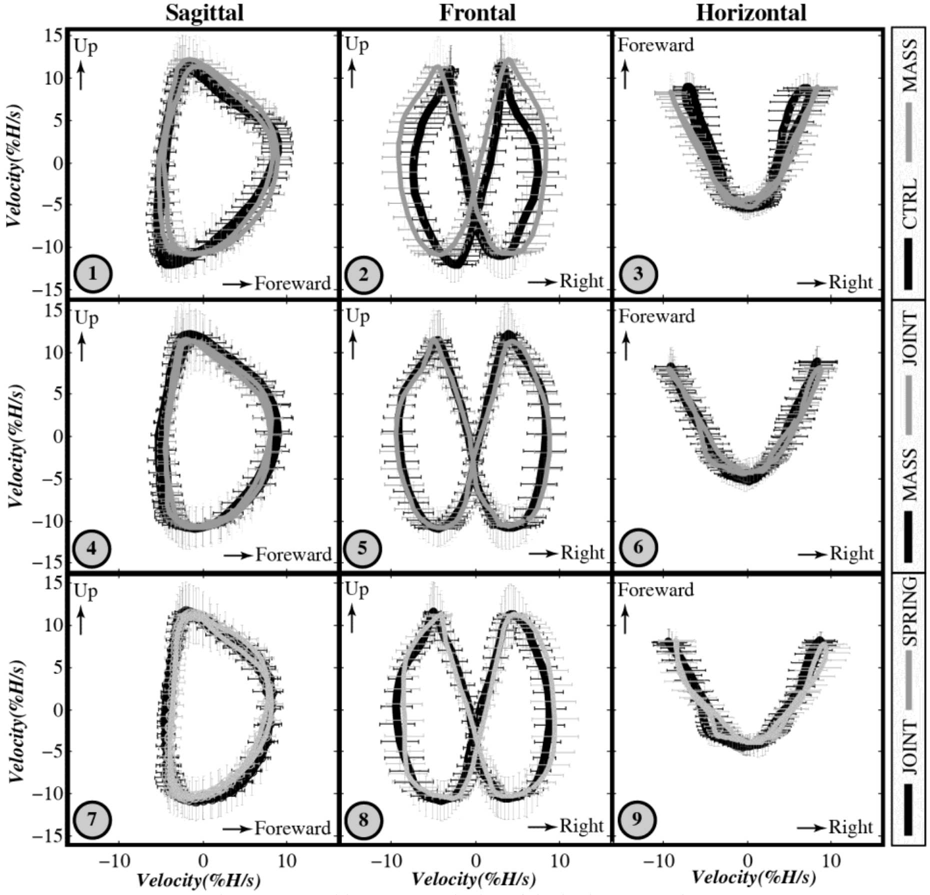

Fig. 7. Inter-subject mean velocity of the body center of mass

show that the exoskeleton joint does not have a significant effect on the travel profile of the COM except for a non-significant decrease (Slope = 0.91 and 0.96) in the range of travel along the anteroposterior and vertical directions. Fig. 6 and 7 show that the exoskeleton joint does not impose noticeable changes on the travel and velocity trajectories of the COM. Fig. 8 shows that the exoskeleton joint did not affect the total mechanical work but resulted in a slight non-significant decrease in the mechanical efficiency.

Effect of Exoskeletal Spring: Graphs 7 to 9 of Fig. 5 show that there were no significant changes in the COM travel profile as a result of the exoskeletal stiffness; however, the exoskeleton stiffness resulted in slight increases in the range of travel of the COM along the mediolateral direction (Slope = 1.04) and slight decrease along anteroposterior (Slope = 0.92) and vertical (Slope = 0.98) directions. Graphs 7 to 9 of Fig. 6 and 7 show that the travel and velocity trajectories of the COM remained relatively invariant under the effect of exoskeletal stiffness. Fig. 8 shows that the total mechanical work and efficiency slightly decreased in SPRING condition when compared with the JOINT condition.

V. CONCLUSIONS AND DISCUSSION

This paper reports the effects of mass, joint, and assistance of a quasi-passive knee exoskeleton on the motion time profiles and planar trajectories of the human body center of mass (COM). The results show that the exoskeleton mass significantly distorted the motion of the COM; whereas, the exoskeleton joint and spring did not significantly affect the motion of the COM. It was also shown that there were also trends present indicating that the exoskeleton mass increased the total mechanical work and the exoskeleton spring assistance decreased the total mechanical work.

The findings of this paper give insights to the human interaction with exoskeletal systems. Firstly, the human body can fully/partially adapt to the assistance of a parallel spring in the stance phase such that the overall motion of the COM remains invariant which, in addition to the findings of others [34], illustrate the human gait adapts to stiffnesses externally applied in parallel and series with the human leg. This also implies that the effects of the parallel spring remains local to the knee joint without affecting the motion of the entire body. This finding is in agreement with the results of others that found the motion of the COM is not correlated with the knee joint behavior in the stance phase [35].

Secondly, external mass added to the lower limbs can change the motion of the COM. This change is mostly pronounced in the mediolateral direction and to a lesser extent in the anteroposterior directions. Interestingly, the vertical motion of the COM tends to remain invariant under the effect of the exoskeleton mass, joint, and spring assistance, which can be attributable to energy recovery. In other words, the human body tends to direct the effects of added mass to fluctuations in horizontal kinetic energy and retain invariant vertical motion profiles to minimize fluctuations in the potential energy.

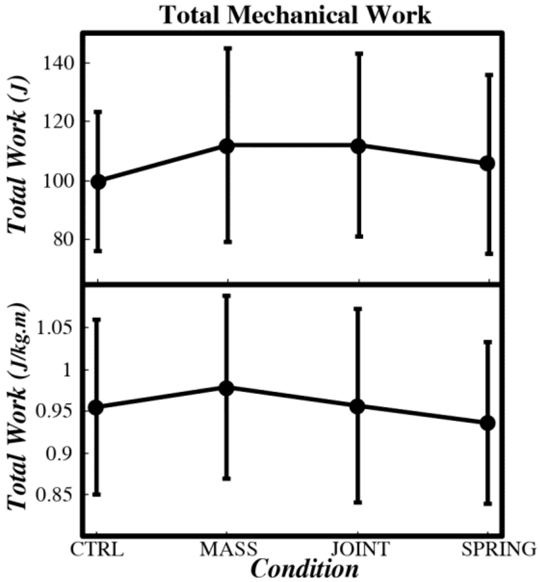

Fig. 8. Top: Total mechanical work carried out on the center of mass, Bottom: Total mechanical work per unit mass per unit distance as a measure of efficiency of walking

There are other knee joint designs that rely on four-bar linkages and consider the variable rotation axis of knee joint. In this study, it was found that the exoskeleton uniaxial joint does not perturb the motion of the COM, implying that a uniaxial joint can be a viable design choice for the knee exoskeletons. The independence of the motion of the COM to the exoskeleton uniaxial joint could be attributable to the redundancy in the lower extremity joints.

The results of this research are also insightful for the design of lower extremity exoskeletons. Firstly, minimization of the exoskeleton mass should be considered in the design process so that the developed device minimally perturbs the motion of the COM, which could lead to unstable and energetically inefficient gait. In fact, using heavy weight exoskeletons can lead to low lateral stability in the gait of the user. Secondly, a uniaxial design (i.e. a simple pivot joint) for the exoskeleton knee joint is a viable design option in regard to motion of the COM. Lastly, assistance of the knee joint in the stance phase using a parallel spring is a reasonable design option mainly because: a. the total mechanical work decreases, b. the effect of assistance remains local to the joint, and c. the lower extremities can adapt to accommodate the external spring and result in minimal changes in the motion of the COM.

In addition to the detailed examination of the joint-level mechanics and the overall energetics of wearers of our exoskeleton prototypes, our future research will focus on the effects of the exoskeleton performance on the motion profiles of the lower extremity joints. We intend to identify the mechanism through which the human body adapts to parallel exoskeleton devices so that the overall motion of the COM remains invariant.

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