

# A Preliminary Assessment of Legged Mobility Provided by a Lower Limb Exoskeleton for Persons With Paraplegia

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**Abstract**—This paper presents an assessment of a lower limb exoskeleton for providing legged mobility to people with paraplegia. In particular, the paper presents a single-subject case study comparing legged locomotion using the exoskeleton to locomotion using knee–ankle–foot orthoses (KAFOs) on a subject with a T10 motor and sensory complete injury. The assessment utilizes three assessment instruments to characterize legged mobility, which are the timed up-and-go test, the Ten-Meter Walk Test (10 MWT), and the Six-Minute Walk Test (6 MWT), which collectively assess the subject’s ability to stand, walk, turn, and sit. The exertion associated with each assessment instrument was assessed using the Physiological Cost Index. Results indicate that the subject was able to perform the respective assessment instruments 25%, 70%, and 80% faster with the exoskeleton relative to the KAFOs for the timed up-and-go test, the 10 MWT, and the 6 MWT, respectively. Measurements of exertion indicate that the exoskeleton requires 1.6, 5.2, and 3.2 times less exertion than the KAFOs for each respective assessment instrument. The results indicate that the enhancement in speed and reduction in exertion are more significant during walking than during gait transitions.

**Index Terms**—Assessment, assistive technology, knee–ankle–foot orthoses (KAFO), leg braces, legged mobility, lower limb exoskeleton, paraplegia, powered orthosis, spinal-cord injury (SCI).

## I. INTRODUCTION

ONE OF THE MOST significant impairments resulting from paraplegia is the inability to stand and walk [1]. In addition to diminished mobility, the inability to stand and walk

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entails significant health consequences, including loss of bone mineral content, frequent skin breakdown problems, increased incidence of urinary tract infection, muscle spasticity, impaired lymphatic and vascular circulation, impaired digestive operation, and reduced respiratory and cardiovascular capacities [2].

In an effort to restore legged locomotion to individuals with paraplegia, several computer-controlled lower limb orthoses have been, and are being, developed and described in the research literature. Such orthoses include hybrid functional electrical stimulation (FES)-systems, which supplement FES of leg muscles with a computer-controlled orthosis; and fully powered orthoses (or exoskeletons), which utilize electric motors as the primary form of motive assistance. Recent examples of the former include those described in [3]–[7], while recent examples of the latter include those described in [8]–[16].

Despite the number of emerging systems designed to provide legged mobility assistance for individuals with paraplegia, there is currently a lack of published data by which the efficacy of each can be quantitatively and comparatively assessed. That is, although several such mobility assistance systems have been characterized, each system has generally been characterized using different metrics. The absence of standardized metrics is a significant impediment with regard to uniformly and comparatively assessing the capabilities provided by a given system, or with regard to assessing the capabilities of a given system relative to unpowered assistive devices, such as leg braces or knee–ankle–foot orthoses (KAFOs). This paper incorporates a combination of predominantly standardized assessment instruments to assess the mobility and level of exertion associated with the legged mobility provided by a powered lower limb exoskeleton, in addition to the legged mobility and exertion afforded by KAFOs (regarded here as the current standard of intervention for legged mobility for individuals with paraplegia).

## II. ASSESSMENT METRICS

### A. Assessment Metrics Used in Prior Studies

A number of different metrics have been used in prior studies to indicate the efficacy of assistive devices and systems in providing legged mobility to subjects with complete spinal-cord injury (SCI). In [17], the authors characterize mobility provided by passive orthoses with average walking speed, and exertion via change in heart rate normalized to walking speed, a measure known as the Physiological Cost Index (PCI). In [18], the

authors also characterize the mobility and exertion provided by passive orthoses with mean walking speed and PCI, and additionally measured oxygen uptake (and found good correlation between PCI and oxygen uptake as measures of energy expenditure). In [19]–[21], the authors assess the mobility provided by an FES-aided gait system (i.e., an early version of the Parastep system) by measuring mean stride characteristics (e.g., stride time and length, relative proportions of single and double support phases, etc.) and mean walking velocity, and assess exertion by measuring the proportion of body weight carried by the legs relative to the arms, and by measuring heart rate and oxygen uptake during walking. In [22] the authors characterize mobility provided by the Parastep FES system by reporting average walking speed and PCI. In [23], the authors assess the mobility of the Parastep system by reporting distance walked and mean walking speed. In [24], the authors assess the mobility provided by the Parastep system by reporting the mean walking distance without rest and the mean walking velocity, and assess exertion by reporting heart rate and oxygen uptake during walking. In [4], the authors indicate the ability of a hybrid-FES system to provide legged mobility to an SCI subject by showing the variation in knee joint angle kinematics over a number of strides. In [7], the authors indicate the efficacy of a hybrid-FES system in providing legged mobility by reporting average walking speed; percent increase in heart rate and blood pressure; oxygen uptake and carbon dioxide exhalation; and variation in hip and knee joint angle kinematics over a number of strides. In [8], the authors assess the efficacy of a powered orthosis, relative to a passive reciprocating gait orthosis, by reporting average walking speed; average step length; and the vertical and lateral motion amplitude of each subject's head. In [10], the authors quantitatively characterize the efficacy of a powered lower limb exoskeleton primarily by characterizing the walking speed. In [10], the authors use heart rate, respiration rate, skin color, and perspiration levels to qualitatively assess level of exertion; the ability to maintain eye contact to qualitatively assess cognitive effort; and the ability to catch a ball to qualitatively assess standing stability. In [11] and [14], the authors evaluated the ability of a powered lower limb exoskeleton to provide sit-to-stand and stand-to-sit maneuvers to a paraplegic user by reporting the hip and knee joint angles during these maneuvers, and also by reporting the force exerted by the user's arms on a horizontal bar. In [25], the authors demonstrate the ability of a powered exoskeleton to provide walking by comparing hip and knee joint kinematics to healthy kinematics, and by reporting average walking speed. Most recently, in [26], the authors use the combination of two standardized assessment instruments [the Ten-Meter Walk Test (10 MWT) and Six-Minute Walk Test (6 MWT)] to assess the mobility of paraplegic subjects walking with a powered exoskeleton. The authors also report heart rate and blood pressure changes, but do not associate those measurements with a specific protocol.

### *B. Standardized Assessment Instruments for SCI Ambulation*

As evidenced by the previous section, there is a general lack of uniformity in the assessment of assistive devices that provide legged mobility to people with complete SCI. In this paper, the authors incorporate a set of standardized assessment

instruments that are collectively intended to characterize the degree of mobility provided by, and level of exertion associated with, lower limb orthoses during standing, sitting, turning, and walking activities, which together constitute the basic components of legged mobility. The intent of the assessment metrics utilized here is to provide an assessment of mobility and exertion in various essential aspects of legged mobility with a set of standardized metrics that can be performed in a clinical setting, and which do not impose undue burden on the experimental subjects. The rationale for the selection of assessment instruments is described below.

A recent survey of outcome measures for persons with SCI identifies seven primary measures associated with functional ambulation [27], which include the Timed Up and Go (TUG) test, the 10 MWT, the 6 MWT, the Spinal-Cord Injury Functional Ambulation Inventory (SCI-FAI), the Functional Independence Measure (FIM), the Spinal Cord Independence Measure (SCIM), and the Walking Index for Spinal Cord Injury (WISCI-II). Of these, the first three are timed measures, the latter three are categorical assessments of ambulation, and the SCI-FAI has components of both. For purposes of assessing the efficacy of mobility systems for providing legged assistance to individuals with SCI, a measurable standardized metric is preferred relative to a classification, since it largely removes subjectivity from the assessment, and further provides a means of characterizing exertion in addition to mobility. As such, for the purposes of this paper, the measurable assessments (TUG, 10 MWT, and 6 MWT) were favored over the observational assessments (SCI-FAI, FIM, SCIM, and WISCI). With regard to the first of these measurable assessments, the TUG test measures the time required for a subject to stand from a seated position, walk 3 m, turn, walk back 3 m, turn, and return to the seated position. This test, which was originally proposed in [28], has been shown to have high test–retest reliability as a mobility measure across a wide spectrum of patient populations, including persons with stroke impairment, Parkinson's disease, arthritis, cerebellar disorders, and unilateral lower limb amputation [28]–[33]. The 10 MWT measures the time for a patient to walk 10 m, not including any acceleration or deceleration phases. Like the TUG test, the 10 MWT has also been shown to have a high degree of validity and test–retest reliability in assessing the functional mobility of persons with neurological mobility impairment [34]–[37]. Finally, the 6 MWT measures the distance a person can walk in 6 min. This test is ideally performed using a straight walkway approximately 30 m long (e.g., a hallway), where the subject turns around a marker following every 30 m length. This measure was originally proposed to assess cardiovascular and respiratory capacity in persons with heart or lung diseases [37], [38], but has also been utilized as a functional mobility assessment for persons with neurologically impaired mobility [39]–[41].

Since the TUG test is the only one of the aforementioned timed assessments that encompasses sit-to-stand, stand-to-sit, turning, and walking; since these movements constitute the basic set of legged mobility functionality; and since the TUG test has been shown to have a test–retest reliability correlation coefficient of 0.98 among the SCI population [37], the TUG test was selected as one independent measure for characterizing

legged mobility systems for SCI. Further, since the TUG test is used across a wide range of impairments, it offers the added benefit of comparison of the SCI target population to a broader patient population.

While the TUG test largely characterizes the ability of a subject to perform functional transitions (sit-to-stand, stand-to-walk, walk-to-stand, turn in place, and stand-to-sit), the 10 MWT and the 6 MWT largely characterize a person's (essentially steady state) walking speed. Like the TUG test, both measures have been demonstrated to have a high test-retest correlation coefficient (both approximately 0.98) [37]. Although both tests provide some measure of walking speed, the 10 MWT provides walking speed without regard to endurance, while the 6 MWT provides a measure of speed over a longer period of time and distance. Further, the 6 MWT includes turns, while the 10 MWT contains only straight-line walking. As such, the authors include both the 10 MWT and 6 MWT in the assessment of the efficacy of lower limb gait assistance systems. Thus, the mobility of the lower limb gait assistance system is characterized here by the combination of the average time required to complete a TUG test, the average time required to complete a 10 MWT, and the average distance covered in a 6 MWT. Each of these three assessment instruments provides unique information about a given aspect of mobility. The TUG test provides a quantitative measure primarily characterizing the ability to perform gait transitions; the 10 MWT provides a quantitative measure primarily characterizing the speed of steady-state walking over a relatively short distance; while the 6 MWT provides a quantitative measure primarily characterizing the speed of steady-state walking over a comparatively long distance, and also generally includes turning.

As used in their respective standard forms, none of these instruments provides a direct measure of the level of exertion associated with each. A measure of exertion is clearly important in characterizing the efficacy of lower limb gait assistance systems. Perhaps more importantly, one would expect that the previously described measures of mobility all have some dependence upon the degree of exertion. That is, one would expect that a subject could presumably perform better on any given mobility test with an increased degree of effort. Thus, by quantifying exertion, one can additionally construct a normalized measure of mobility to exertion, which is likely to provide a more invariant indication of system performance than either taken alone.

Oxygen uptake is a well-established means of characterizing exertion during legged mobility. Such measurement, however, requires laboratory instrumentation that is not generally available in a clinical setting, which presents a barrier with respect to standardization. Further, such instrumentation can be cumbersome, and is not entirely suitable for use with patients with complete SCI. In order to circumvent these issues, alternative assessments of exertion based on heart rate have been described. Two commonly used measures are the Total Heart Beat Index (THBI), as described in [42], and the PCI, as described in [43]. The former measure (THBI) has been shown to be highly correlated with oxygen uptake [42]. However, THBI requires that heart rate be monitored continuously during the activity being characterized, which is not unduly burdensome,

but also presents a barrier to standardization. The PCI is similar to the THBI, but does not require a continuous measurement of heart rate. Rather, the PCI requires a single measurement that is intended to characterize an average (ideally steady-state) heart rate, and characterizes exertion by the change in heart rate (relative to resting), normalized by average walking speed. Although not as highly correlated with oxygen uptake as the THBI, the PCI has been shown to be correlated with oxygen consumption measures [43]–[45], and as previously described has been used in previous assessments of legged mobility devices for people with complete SCI [17], [18], [22]. Since the PCI provides a simple measure of exertion based on standard clinical instrumentation (i.e., a standard heart-rate monitor), the PCI method was incorporated here. Specifically, each assessment instrument was accompanied by measurement of the pre- and post-test heart rate, where the pre-test heart rate corresponded to a resting condition. All heart rates were taken with an automated heart monitor. For purposes of repeatability, the post-test rates were taken thirty seconds after the completion of each respective mobility test.

The PCI was calculated for each assessment instrument using the average speed for each test, where the TUG test nominally represents a distance of six meters. Thus, the proposed assessment of a powered legged assistance system for persons with SCI requires the subject to perform three standardized assessment instruments (the TUG test, the 10 MWT, and the 6 MWT). The essential mobility provided by the system is characterized by the time required to complete the TUG test and 10 MWT, and the distance completed in the 6 MWT; the exertion required by the system is characterized by the change in pre- (resting) and post- (at 30 s following completion) heart rates; and the speed-normalized exertion is given by the change in heart rate normalized by the average speed of the activity.

### III. COMPARATIVE ASSESSMENT OF A POWERED LOWER LIMB EXOSKELETON

The previously described assessment procedure was employed by the authors to comparatively assess the efficacy of a powered lower limb exoskeleton system in providing legged mobility relative to the use of KAFOs. Testing was performed with a paraplegic subject with a T10 motor and sensory complete injury, American Spinal Injury Association, ASIA, A classification. With both the exoskeleton and the KAFOs the subject used a walker as a stability aid. Specifically, the subject was able to use either a walker or forearm crutches with the powered exoskeleton, but was unable to use forearm crutches with the KAFOs. As such, in order to provide a better controlled comparison, the subject used a walker for both devices in all assessments described herein. The mass of the walker used was 3.5 kg (7.8 lb).

#### A. Lower Limb Exoskeleton

The powered lower limb exoskeleton used in the assessment, shown in Fig. 1, provides powered assistance in the sagittal plane at both hip and knee joints. The exoskeleton consists of a hip segment, a right and left thigh segment, and a right and left shank segment. The hip segment contains a lithium polymer battery which powers the exoskeleton, and each thigh segment



Fig. 1. Vanderbilt lower limb exoskeleton.

contains a pair of brushless dc motors, which actuate the hip and knee joints respectively through speed reduction transmissions. The knee joints are additionally equipped with normally-locked brakes, in order to preclude knee buckling in the event of a power failure. Although the exoskeleton does not explicitly contain a foot segment or ankle joint, it is designed to be used in conjunction with a set of standard ankle foot orthoses (AFOs), which provide stability at each ankle, and preclude foot drop during the swing phase of gait. The total mass of the exoskeleton, including the battery, is 12.3 kg (27 lb). A more detailed description of the exoskeleton design, including a description of the embedded electronics system, is given in [25].

The powered lower limb exoskeleton enables sit-to-stand transitions, standing, stand-to-walk transitions, walking, walk-to-stand transitions, and stand-to-sit transitions. In order to enable the user to have autonomous control of these maneuvers, a user interface was developed based on the user's ability to affect his or her center of pressure via the use of his or her

upper body, in combination with a stability aid. Specifically, based on sensors embedded in the exoskeleton, the control system estimates the location of the user's center of pressure (CoP), defined as the user's center of mass projection onto the horizontal ground plane, and uses the distance between the CoP and the location of the forward ankle joint as the primary command input. Thus, the user transitions out of a given activity (sitting, standing, or walking) by tilting his or her body forward or back, such that the CoP moves in an anterior or posterior direction, which commands the controller to transition to a different activity mode. This approach enables the user to autonomously perform the various tests described here without the assistance of an external operator. A more detailed description of the exoskeleton control architecture and user interface, which discusses more specifically the conditions required to move between activities, is given in [46]. Finally, note that the turning maneuver (performed twice in each TUG test and also in the 6 MWT) does not entail a separate control mode, but rather is performed in the standing activity mode, with the use of the stability aid, by incrementally twisting the upper body and turning in place. This follows the typical turning methodology utilized with KAFOs, which is described in the discussion below.

### B. Ambulation With KAFOs

KAFOs are the most common legged mobility aids used by persons with paraplegia. The KAFOs used in this case study, which are representative of this type of mobility aid, are shown in Fig. 2. These KAFOs consist of a thigh segment, shank segment, and integrated shoe for each leg. The total mass of the KAFOs is 5.7 kg (12.5 lb). The knee joint of each leg consists of a latching hinge joint, such that the joint can remain flexed while donning or sitting, but mechanically locks at full extension, and remains locked during use. Following use, the user can unlatch the knee joints with the posterior lever, which facilitates a more natural seated posture, and simplifies the doffing procedure. Most KAFOs incorporate posterior bail locks, which release the knees as the metal bail (located behind and slightly above the knee) is forced upward by the edge of a seat as the user leans backwards during the transition from standing to sitting. In addition to locking knee joints, each leg of the KAFOs incorporates an articulated ankle joint, which allows limited ankle dorsiflexion, but precludes ankle plantarflexion.

As does the exoskeleton, KAFOs such as those shown in Fig. 2 require the use of a stability aid (most commonly a walker). A user can achieve a reciprocal gait by alternately leaning left and right while simultaneously leaning forward, which unweights the swing leg such that gravity can act to swing the leg forward. A typical sit-to-stand maneuver with KAFOs starts with the subject seated in a chair, with the knee joints fully extended and locked, with the legs fully extended in front of the user, and the heels of the shoes in contact with the ground. Using a walker as a stability aid, as was the case with the assessments reported here, the user pushes upward in the walker, such that his or her legs are drawn up through the walker, until in a fully upright position. A typical stand-to-sit maneuver requires that the user position him or herself in front of a chair, bend forward at the waist, and essentially fall backward into the chair as the chair



Fig. 2. KAFOs used in assessments. Note that the spreader bar attached at the ankles is removed during reciprocal use.

lifts the bail locks, unlocking the knees. Finally, turning in place is afforded by incrementally rotating the stability aid by twisting the upper body, then unweighting the legs to reorient them with the upper body and stability aid. Using this method, a user can typically turn 180° in three or four increments with a walker.

#### IV. ASSESSMENT METHODS

The efficacy of the powered lower limb exoskeleton was assessed using the previously described metrics, and compared to the respective metrics associated with KAFO ambulation. These assessments were performed on a single paraplegic subject with a T10 motor and sensory complete injury (ASIA A classification). The subject was 42 years of age, 10 years post-injury, 1.85 m (6 ft) tall, and with a body mass at the time of testing of 75 kg (165 lb). The subject is shown wearing the lower limb exoskeleton and KAFOs, respectively, in Fig. 3. At the time of testing, the subject had nine years of experience walking with the KAFOs using a walker, typically walking short distances for exercise one to three times per week. The subject had used the exoskeleton approximately 20 times prior to this testing over



Fig. 3. Paraplegic subject wearing Vanderbilt exoskeleton (left) and KAFOs (right).

the span of one year, typically spending 4–6 h walking intermittently with the device. Although randomization between cases would have been desirable, the authors did not feel that the need for randomization justified the subject having to don and doff KAFOs and the exoskeleton multiple times during the testing series. As such, the KAFO assessments were conducted first, followed by the exoskeleton assessments. It was assumed that, if fatigue was a factor, it would adversely affect the exoskeleton results more than the KAFO results. The subject performed the TUG tests first, followed by the 10 MWT, followed by the 6 MWT. Each successive test was performed after the subject's heart rate returned to a resting condition. Although no external assistance was provided to the subject during any of the tests, all tests involved the use of a gait belt and close monitoring by a trained physical therapist, as per the Institutional Review Board approval corresponding to these assessments.

##### A. TUG Test Protocol

The authors followed the protocol described in [28] for the TUG tests. Specifically, the floor was marked with two lengths of tape placed 3 m (10 ft) apart, which designated the starting position and turning position, respectively. A wheelchair with locked wheels and with footrests removed was used in place of a conventional chair for the TUG test, and was positioned fully behind the starting position. The subject was instructed to wait for the verbal cue to start, then stand, walk until he crossed the turning mark, turn, walk back to the chair, turn, and sit. The total time was recorded from the initial verbal cue, to the time the subject returned to a seated position in the wheelchair.

In order to standardize heart rate measurement, each TUG test was not initiated until the heart rate of the seated subject was at



a resting rate (as determined in a clinically standard manner). The post-test heart rate was taken 30 s after the completion of each TUG test (i.e., 30 s after the subject returned to a seated position). The heart rate measurement was taken with an automated monitor (Dynamap V100, General Electric), which required approximately 20 s from initiation (i.e., donning of finger clip) to measurement (i.e., the post-test heart rate measurement was initiated 30 s after TUG test completion, and reported approximately 50 s after TUG test completion, such that the rate is the average heart rate taken between 30 and 50 s after test completion). Prior to the first recorded measurement, the subject was allowed to practice the TUG test until he felt comfortable performing it. Once the subject was comfortable performing the TUG test, the test and associated heart rate measurements were performed three times. The subject rested between each test until his heart rate returned to a resting level.

### B. 10 MWT Protocol

For the 10 MWT, the floor was marked with two lengths of tape placed 10 m (33 ft) apart. In this test, the subject ambulated at a steady-state through the 10 m walkway (i.e., the subject started walking several meters prior to the first mark, and continued to walk through the second mark. The subject was instructed to walk at a “normal comfortable speed.” As with the TUG test, each 10 MWT was not initiated until the subject was seated with a heart rate at resting level. The starting and ending times were recorded based on the subject’s body crossing the respective marks. Following crossing of the second mark, the subject immediately sat in a wheelchair. The subject’s post-test heart rate was taken while seated, 30 s after crossing the second mark. As with the TUG test, the subject completed the 10 MWT three consecutive times, resting between each until his heart rate returned to his resting rate.

### C. 6 MWT Protocol

The 6 MWT was performed in a straight hallway, in which two cones were spaced 30 m apart. The subject was instructed to “cover as much ground as possible in six minutes” by walking back and forth, turning around each cone as each is reached. For each case (of legged mobility assistance), the subject completed the test three times. Each test started with the subject seated at a resting heart rate, although the timer was not started until the subject was standing and ready to walk. After 6 min, the subject was seated, and his post-test heart rate was measured 30 s following the completion of each test.

## V. RESULTS AND DISCUSSION

The results of the assessment for the KAFOs and exoskeleton are summarized respectively in Tables I–III. A video is provided with the supplemental material that shows a representative TUG test with the exoskeleton and with the KAFOs, respectively, which is intended to provide a qualitative sense of the legged mobility provided by each. Each of the previously discussed mobility, exertion, and efficiency measures are discussed below. Note that a paired-sample *t*-test was performed for all data, using a 90% confidence level (unless otherwise

TABLE I  
SUMMARY OF MOBILITY DATA, AVERAGE AND (STANDARD DEVIATION)  
OF THREE TRIALS

Form of mobility assistance	TUG test time (s)	10MWT time (s)	6MWT distance (m)
KAFOs	111 (5.8)	96 (5.3)	37 (1.9)
Exoskeleton	96 (6.6)	58 (3.1)	64 (4.5)

TABLE II  
SUMMARY OF EXERTION DATA, AVERAGE AND (STANDARD DEVIATION)  
OF THREE TRIALS

Form of mobility assistance	TUG Heart rate increase (beats/min)	10MWT Heart rate increase (beats/min)	6MWT Heart rate increase (beats/min)
KAFOs	25 (2.9)	17 (6.0)	18 (5.2)
Exoskeleton	10 (7.0)	5 (1.5)	10 (4.6)

TABLE III  
SUMMARY OF PCI, AVERAGE AND (STANDARD DEVIATION)  
OF THREE TRIALS

Form of mobility assistance	TUG test efficiency (beats/m)	10MWT efficiency (beats/m)	6MWT efficiency (beats/m)
KAFOs	7.7 (0.79)	2.69 (0.83)	2.97 (0.93)
Exoskeleton	4.73 (1.95)	0.52 (0.18)	0.92 (0.38)

noted in the discussion) to ascertain the extent to which the differences in average values of each measure (for the exoskeleton and KAFOs, respectively) was statistically significant.

### A. Mobility

The principal measures of mobility are the TUG test time, 10 MWT time, and the 6 MWT distance. The averages and standard deviations across three trials for each measure, for the KAFOs and exoskeleton, respectively, are listed in Table I. A comparison of the average times across three trials of the TUG test and 10 MWT, respectively, for the KAFOs and exoskeleton, respectively, is shown graphically in Fig. 4. Both differences were significant (at a 90% confidence level), based on the paired-sample *t*-test. Fig. 5 shows the relative performance of the KAFOs and exoskeleton on the 6 MWT, where the difference was also statistically significant, based on the paired *t*-test, at the same confidence level. If all three results are instead characterized by an average speed (where the TUG distance is considered 6 m), the average locomotion speed corresponding to each assessment for the KAFO locomotion was 0.050, 0.10, and 0.10 m/s for the TUG, 10 MWT, and 6 MWT, respectively, while the average locomotion speed for the exoskeleton was 0.063 m/s, 0.17 m/s, and 0.18 m/s, respectively. The relative speeds for each intervention and assessment are shown graphically in Fig. 6. Based on these measures, the TUG test was on average performed 25% faster with the exoskeleton relative to the KAFOs, and the 10 MWT and 6 MWT were on average performed 70% and 80% faster, respectively, with the exoskeleton. Note that both the 10 MWT and 6 MWT essentially provide measures of walking speed, and both similarly indicate that the exoskeleton provides approximately a 70%–80% increase in walking speed relative to KAFOs. The difference in TUG test times, however, is not as substantial, since the TUG test primarily characterizes

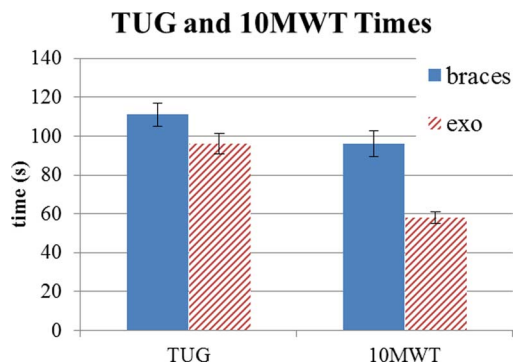


Fig. 4. Average time from three trials of TUG test and 10 MWT with KAFOs and exoskeleton, respectively. Error bars indicate one standard deviation from the average.

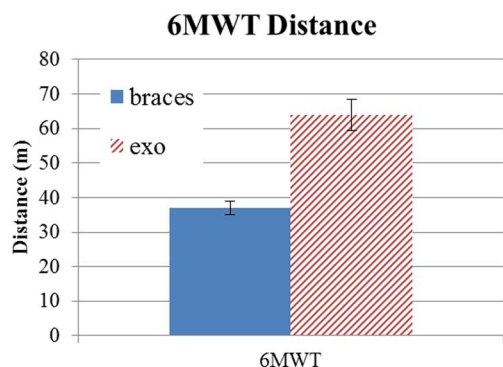


Fig. 5. Average distance of three trials of 6 MWT with the KAFOs and exoskeleton, respectively. Error bars indicate one standard deviation from the average.

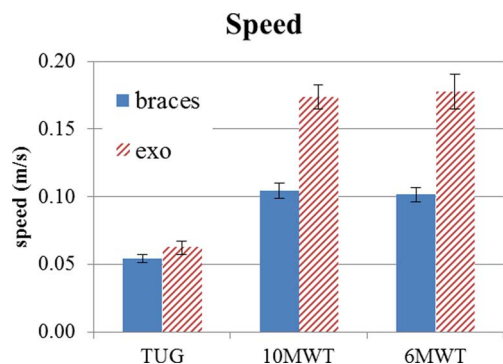


Fig. 6. Average speed with KAFOs and exoskeleton, respectively. Error bars indicate one standard deviation from the average.

the nature of gait transitions (i.e., sit-to-stand, stand-to-sit, and turning) rather than steady-state walking speed.

### B. Heart Rate

The principal measure of exertion as proposed here is the difference in heart rate between pre- and post-test measurements (i.e., the heart rate increase), where the former is a resting rate, and the latter is measured at the completion of each respective test (technically 30 s after completion). The average heart rate increases, and corresponding standard deviations, across the three trials of each test, for the KAFOs and exoskeleton, respectively, are listed in Table II, while a graphical comparison

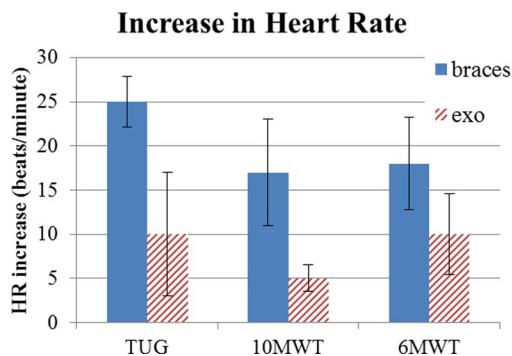


Fig. 7. Average increase in heart rate for all tests with the KAFOs and exoskeleton, respectively. Error bars indicate one standard deviation from the average.

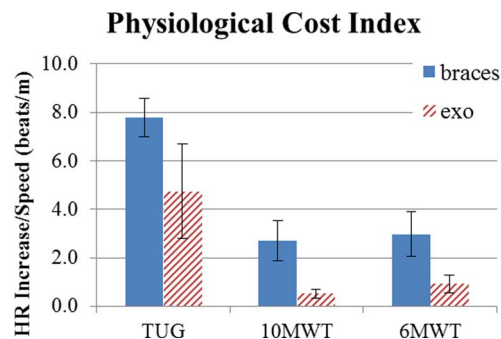


Fig. 8. Average PCI for all tests with the KAFOs and exoskeleton, respectively. Error bars indicate one standard deviation from the average.

of these values is shown in Fig. 7. As seen in the figure, in all cases the level of exertion (specifically the increase in heart rate) is lower when using the exoskeleton relative to using KAFOs. In all cases, these differences are statistically significant with a 90% confidence level, except in the case of the 6 MWT, in which case the difference is statistically significant with an 85% confidence level.

### C. Exertion

As previously discussed, the level of exertion required by each assistive device to perform each assessment instrument was characterized by the PCI. Based on the average speeds (Fig. 6) and the heart rate data (Table II), the PCI corresponding to each assessment instrument and assistive device is listed in Table III, along with corresponding standard deviations. Note that units of speed were converted to m/min in the calculation of PCI order to be consistent with the unit of time used for the heart rate measure. A graphical comparison of these values is given in Fig. 8. As seen in the figure, in all cases the level of exertion was smaller with the exoskeleton than with the KAFOs. Specifically, the level of exertion with the KAFOs in the TUG, 10 MWT, and 6 MWT was 1.6, 5.2, and 3.2 times greater than with the exoskeleton, respectively. In all cases, the differences are statistically significant with a 90% confidence level. Note that these results indicate that the reduction in exertion entailed in ambulation with the exoskeleton is more substantial during walking than during mobility transitions (i.e., sit-to-stand, stand-to-sit, and turning). Specifically, in order of least to greatest difference

in exertion, the TUG test (1.6 times less exertion than KAFOs) consists primarily of transitions; the 6 MWT (3.2 times less exertion) includes some transitions (i.e., turns at each cone), but consists primarily of walking; and the 10 MWT (5.2 times less exertion) consists entirely (and purely) of walking (with no transitions). In other words, the difference in exertion of the respective activity (between the exoskeleton and KAFOs) is lessened as the activity involves more transitions. Qualitatively, the exertion required for sit-to-stand is lessened with the exoskeleton relative to the KAFOs, while the exertion required for turning and stand-to-sit transitions is similar for both devices.

## VI. CONCLUSION

In this paper, the authors assess the efficacy of legged mobility using a powered lower limb exoskeleton, relative to the efficacy of legged mobility with KAFOs. Specifically, the authors incorporate three standard assessment instruments, which are the TUG test, 10 MWT, and 6 MWT. Using these assessment instruments, the authors assess mobility and exertion. These assessments suggest that walking with the exoskeleton provides increase in walking speed and a concomitant decrease in required exertion relative to walking with the KAFOs.

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