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Research Article

Mina: A Sensorimotor Robotic Orthosis for Mobility Assistance

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While most mobility options for persons with paraplegia or paraparesis employ wheeled solutions, significant adverse health, psychological, and social consequences result from wheelchair confinement. Modern robotic exoskeleton devices for gait assistance and rehabilitation, however, can support legged locomotion systems for those with lower extremity weakness or paralysis. The Florida Institute for Human and Machine Cognition (IHMC) has developed the Mina, a prototype sensorimotor robotic orthosis for mobility assistance that provides mobility capability for paraplegic and paraparetic users. This paper describes the initial concept, design goals, and methods of this wearable overground robotic mobility device, which uses compliant actuation to power the hip and knee joints. Paralyzed users can balance and walk using the device over level terrain with the assistance of forearm crutches employing a quadrupedal gait. We have initiated sensory substitution feedback mechanisms to augment user sensory perception of his or her lower extremities. Using this sensory feedback, we hypothesize that users will ambulate with a more natural, upright gait and will be able to directly control the gait parameters and respond to perturbations. This may allow bipedal (with minimal support) gait in future prototypes.

1. Introduction

The limited mobility assistance options for those suffering from paraplegia or paraparesis typically utilize wheeled devices, which require infrastructure (ramps, roads, smooth surfaces, etc.), and 69.8% of spinal cord injured (SCI) paraplegics use a manual wheelchair as their primary means of locomotion, which limits range and terrain options [1]. Wheeled conveyances allow access to only a small fraction of the locations accessible to pedestrians. Wheelchairs have trouble on curbs, stairs, irregular terrain such as hiking trails and narrow corridors. Even with advances in powered wheelchairs, such as the iBot (http://www.ibotnow.com/), mobility remains limited to relatively smooth terrain, precluding access to much of the natural outdoors. Additionally, being confined to a wheelchair has significant consequences on physiological and psychological health, quality of life, and social interactions. Health-related issues include pressure sores, poor circulation, loss of bone density muscle mass, and changes in body fat distribution [2–4]. Robotic lower extremity orthosis designs can offer new mobility options for those currently limited to a wheelchair, enabling such individuals to regain access to areas that require legged locomotion and to restore the health benefits associated with an upright posture. In addition to improving quality of life as orthotic devices, exoskeletons could also bridge the gap to future regenerative medicine approaches for this population. For example, a paraplegic user of a robotic orthosis could maintain healthy bone and muscle mass and range of joint motion that could reduce rehabilitation time following stem cell therapy.

1.1. Robotic Orthoses. Current robotic assistance devices such as the body-worn ReWalk from Argo Medical Technologies (http://www.argomedtec.com/) and the eLegs from Berkely Bionics (http://berkeleybionics.com/) have motors at the hips and knees to move the legs and provide powered gait. The user provides balance with the aid of forearm crutches and uses torso motions, arm movements, and/or a push button interface. Both devices can operate untethered for several hours on a single charge. Users have demonstrated stair climbing with the ReWalk; however, neither device has demonstrated operations over rough and irregular terrain. Both devices target paraplegic users who cannot initiate any motion of their legs and thus must operate in a rigid position control mode. Use by paraparetics, however, requires a more compliant mode of operation. Both devices are undergoing clinical trials, and neither device is currently available for personal use.

The commercially available hybrid assistive limb (HAL) device, which has significant operational experience with able-bodied users [5], augments user-initiated movement by detecting electromyographic (EMG) signals in the user's lower extremity muscles. A new version of this device, HAL-5 LB (Type C), specifically targets paraplegic users [6], but has only demonstrated transition from sitting to standing, not overground mobility. This design, however, does include an actuator at the ankle, a feature lacking from the ReWalk and the eLegs. The wearable power assist leg (WPAL) [7, 8], another paraplegic gait assist device, relies on a walker rather than crutches for the required balance stabilization. The walker provides a significant support polygon for the user and requires a different, less natural gait. Similarly, the EXoskeleton for Patients and the Old by Sogang University (EXPOS) [9], designed as a walking assist device for the elderly and for patients with muscle or nerve damage in the lower body, uses a wheeled-caster walker to carry the actuators and computer system. It transfers actuator forces to the exoskeleton joint via cables and employs position control of the exoskeleton joints, but it lacks force sensing in the actuators. Force sensors on the leg braces are used to detect the user intent, but the integral caster walker limits operation and utility of this device to smooth floors. Zabaleta et al. [10] also propose to track EMG and utilize compliant actuation for a robotic exoskeleton for rehabilitation.

A number of robotic orthoses developed for treadmill-based operation face some of the same challenges, share some of the same technologies, and they are strictly limited to rehabilitation activities. The Powered Gait Orthosis (PGO) [11] and LOwer-extremity Powered ExoSkeleton (LOPES) [12] utilize force sensors on each actuator, which allows for torque control of the joints. One of the most utilized and studied treadmill-based robotic orthotic devices, the Lokomat [13, 14], has demonstrated the advantages of compliant control strategies [15, 16].

At the Florida Institute for Human and Machine Cognition (IHMC), we have designed and built a robotic orthosis called Mina (Figure 1) to provide overground mobility for paraplegic and paraparetic users. Mina utilizes compliant control actuators and can provide both rigid position control for paraplegic users and assistive force control for paraparetic users. In its current state of development, the prototype Mina offers operates similarly to the ReWalk and eLegs for paraplegic mobility with hip and knee actuation for powered execution of recorded gait. All three devices move the legs through predetermined joint trajectories with strict position control of the exoskeleton joint. However, the compliant control actuators that Mina utilizes facilitate operation over rough terrain.

In addition, Mina provides the user with sensory feedback from the exoskeleton. Sensory feedback provides a key element for motor-control missing from other paraplegic mobility assist devices. SCI users lack body awareness below the level of injury, which makes user control of orthotic devices cumbersome. Reinstating sensory feedback should facilitate the integration of the orthosis into the user's posture and ambulation strategy and, potentially, restoration of bipedal gait for this population.

Figure 1: The IHMC Mina sensorimotor robotic orthosis for mobility assistance prototype. Mina adjusts to fit users ranging from ~1.6 m to 1.9 m tall.

1.2. The Sensory Substitution Paradigm. Because perception occurs in the brain and not at the sensory end organ [17], sensory substitution interfaces can provide an alternative pathway for sensory perception. A sensory substitution system consists of three parts: a sensor, a coupling system, and a stimulator. Sensory substitution can occur across sensory systems such as touch-to-sight or within a sensory system such as touch-to-touch. The human brain, in fact, can reinterpret signals from specific nerves (e.g., from tactile receptors) given appropriate, veridical, and timely sensory feedback. This forms the basis for sensory substitution interfaces that can noninvasively and unobtrusively use alternative, intact sensory pathways. This plasticity inherent to the brain and nervous system supports both long-term and short-term anatomical and functional remapping of sensory data [18, 19] and will assist brain reorganization despite losses in muscle, bone, reflexes and will assist a user's ability to perform activities of daily living [20]. Tactile and proprioceptive feedback sensory substitution technologies have been developed for use with lower limb prostheses [21–24] to provide foot sole pressure information, joint angle, and other forces. Because paralyzed individuals lack proprio- and exteroception from the lower limbs, they must use their vision to monitor "what's going on" below their level of injury. Compensating for the loss of tactile information from the soles, as well as proprioceptive information (i.e., muscle stretch and joint position) visually requires significant cognitive effort that could be redistributed through other sensory modalities. Mina provides similar input for users with intact but paralyzed legs by providing ground reaction forces and proprioceptive signal analogs from the insensate feet. The fundamental challenges for sensory augmentation in an exoskeleton relate to identification of the optimal information for the user when walking and intuitive presentation of that information without increasing cognitive workload or competing with vision or hearing.

1.3. Human Machine Interface (HMI) Considerations. The human motor control system relies on sensory information (feedback) in order to respond to perturbations and stabilize errors. Sensory feedback, for example, enables the brain to maintain the body's posture and helps it to determine the positions of the limbs in space and the amount of force required to execute a movement. Several sensory systems (i.e., the vestibular, visual, and somatosensory systems) contribute to the control of balance and offer an important channel of information that help to coordinate human interaction with the world. The vestibular system gives the sense of whole body orientation and motion in collaboration with the visual system. For both posture and gait, motor control mechanisms seek to hold the body's center of gravity (CG) over the polygon of support (defined by the position of the individual's feet). While determining position of the center of mass under dynamic conditions is hard to compute, the central nervous system can infer its position by using the information provided by the muscle-tendon stretch receptors and the cutaneous pressure receptors of the foot sole. Paraplegia deprives the user of both the motor and sensory functions; restoring mobility requires reinstatement of movement and sensation. The IHMC Mina system displays ground reaction forces and center of pressure, as well as joint positions and torque estimations, using noninvasive tactile interfaces, specifically a BrainPort intra-oral display (Wicab, Inc., Middleton, WI) and a VideoTact abdominal display (ForeThought Development, LLC, Blue Mounds, WI). These displays (Figure 2) interface to the relatively underutilized, with respect to hearing and vision, tactile channel and provide sufficient resolution for the data represented by Mina.

The BrainPort electrotactile transducer array is held in the mouth and connected to battery powered electronics that generate highly controlled electrical pulses that produce patterns of tactile sensations when the electrodes are in contact with the top surface of the tongue. The tongue's sensitivity, excellent spatial resolution, mobility, and distance to the brainstem make it an ideal site for a practical electrotactile HMI. An electrolytic solution (saliva) assures good electrical contact. Perception with electrical stimulation of the tongue appears to be better than with fingertip electrotactile stimulation, and the tongue requires only about 3% (5–15 V) of the voltage, and much less current (0.4–2.0 mA) than the fingertip for electrotactile stimulation [25]. Current BrainPort arrays can provide a 100 to 600 pixel resolution via the intraoral display (IOD) tongue array.

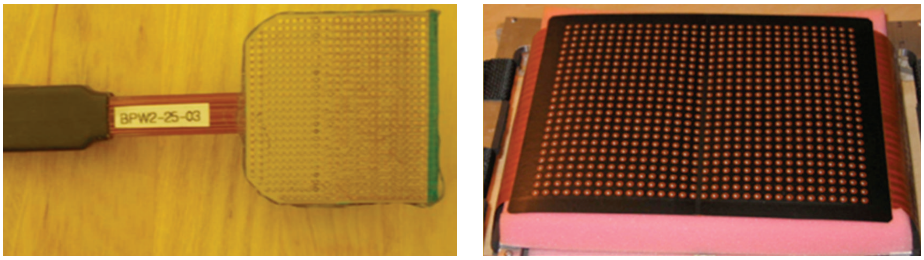
The VideoTact is also an electrotactile interface; however, it is placed on the abdomen. It can exploit the larger surface area of the abdomen to improve spatial separation. While the density of torso sensory receptors is not as high as the tongue, placing a high-resolution display (e.g., 24×32) on the abdomen allows for rapid perception of motion of objects [26] and can be worn discretely under the users clothing. The keratinized layer of dead skin cells of the epidermis on the torso requires the VideoTact to use higher voltage (15–40 VDC) and current (8–32 mA) than the BrainPort; however, it is battery driven and further electrically isolated by storing the stimulus charge in an array of capacitors that are disconnected from the power source prior to stimulus delivery.

Integrating these two displays to provide sensory substitution of proprioception and somatosensation to Mina users should lead to shorter training requirements, improved sense of balance, and sensorimotor reorganization that integrates both perception and control of the exoskeleton. Both devices have intensity control via software with user override for intensity and shut-off. IHMC has used these general-purpose sensory substitution displays previously for augmentation of individuals with balance disorders, as well as for vision and hearing substitution systems. IHMC is currently investigating the effectiveness of various sensory substitution symbologies to provide the user with an effective, intuitive understanding of the state of the exoskeleton with low cognitive demand.

2. Exoskeleton Design

Mina is a second-generation [27] lower extremity robotic gait orthosis with two actuated degrees of freedom per leg, hip flexion/extension, and knee flexion/extension, for a total of four actuators. Mina does not provide hip ab-/adduction or medial/lateral rotation of the leg and employs rigid ankle joint with a compliant carbon fiber footplate. Mina users connect to a rigid back plate, which has a curvature to match that of the human spine, via shoulder and pelvic straps. The system can accommodate a range of body sizes by using nested aluminum tubing as the structural links to attach to the user's thigh, leg, and foot. A tether provides the prototype with power for the computer and motors, as well as Ethernet communication; later versions will integrate battery power and wireless communications technologies for untethered operations. A fall prevention tether connected to an overhead trolley system supports the user and Mina only in the event that the user loses balance or missteps.

2.1. Actuators. Mina uses four identical rotary actuators (Figure 3) capable of both position and torque control. Each actuator consists of a DC brushless motor (Moog BN34-25EU-02) and a 160 : 1 harmonic drive (SHD-20 from HD Systems) gear reduction. The actuators are instrumented with two incremental encoders. One encoder measures the relative position between the motor shaft and the base of the actuator. This encoder (HEDL-5640#A13, Avago Technologies, Inc. San Jose, CA) has a resolution of 2000 counts per revolution, resolving to $1.96e-5$ rad/count at the output. The second encoder (RGH-24, Renishaw, PLC, Gloucestershire, England) measures the relative position between



(a) (b)

Figure 2: Tactile sensory substitution electrotactile displays used by Mina. (a) Wicab BrainPort 600 pixel tongue array; (b) a 768 titanium electrode abdominal array (ForeThought VideoTact).

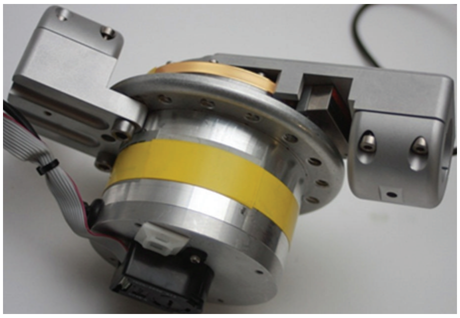


Figure 3: Actuator showing two encoders, golden read strip that is wrapped around the base of the harmonic drive gear reduction.

the output of the actuator and the base of the actuator using a linear encoder with the read-head mounted onto the output of the actuator and the linear encoding strip wrapped around the surface of the harmonic drive input (which is securely fixed onto the base of the actuator). This encoder has a resolution of 1 mm at a radius of 0.45 m, which resolves $2.22e-5$ rad/count.

The motion of the output encoder matches the motion of the motor encoder, minus any elastic deformation of the harmonic drive due to torque applied to the output shaft. By applying a known torque and measuring the deflection using the difference between the two encoders, we characterized the elasticity of each actuator. With a peak torque of about 60 Nm, the elastic deflection is about 0.0025 rad, indicating a stiffness of approximately 24 kNm/rad. In operation, an empirically determined look-up table is used to indicate the torque of the actuator based on harmonic drive deflection.

The Mina operates in position, or high impedance, control using only the motor shaft encoder (Avago HEDL-5640#A13) instead of the output encoder (Renishaw RGH-24) due to occasional loss of counts of the output encoder. Because the deflection of the harmonic drive is considered negligible with regard to the tolerance required on the output position, the simple proportional plus derivative feedback control algorithm only needs the output position to control the motor input current.

A series elastic actuator (SEA) was used in order to achieve torque control. In designing the SEA, the major design element to select is the spring rate, which is dependent on a number of factors, including the resolution of the spring deflection sensor, the maximum speed of the motor, the amount of impact isolation allowed to the gear train, the acceptable reflected inertia at the output, the bandwidth requirements on position and torque control, and complexity of the design. Our application can tolerate a stiff spring due to the inherent impact protection from the connection to the user and requires a stiff spring due to tight positioning requirements. By utilizing high-resolution encoders (approximately $2.0e-5$ radians/count) the design is able to function with a very stiff series spring. We determined that the inherent compliance of the harmonic drive was sufficient for this application and would result in a compact, low part count design. For torque control, Mina uses a simple proportional plus derivative controller (see Figure 4) where the error signal equals desired torque minus the applied torque and is used to determine the input current to the motor. The feedback gains were tuned empirically. The value for K_p was 2.0, and the value for K_d was 0.0002.

2.2. Computer and Electronics. An embedded PC-104 computer system mounted on the back plate, running a Real-Time Java under Solaris (Oracle, Corp., Redwood Shores, CA) and the control software, written in Real-Time Java provides closed-loop control of the actuators via Accelnet digital servo modules (ACM-180-20, Copley Controls, Peabody, MA) and communicates with a desktop host computer via a tethered Ethernet cable. The embedded computer runs the control code, stores the trajectories used for the paraplegic walking-mode and transmits relevant state variables to a host computer in real time (50 Hz) for display and monitoring.

Mina uses F-Scan (Tekscan, Inc., Boston, MA) insoles placed between the footplate and the shoe with up to 960 pressure sensors to detect ground reaction forces and determine center of pressure on each foot (smaller insoles are cut form the standard size, resulting in fewer total sensors). Figure 5 shows the normalized pressure map from the insoles (black = zero pressure, white = normalized maximum recorded during calibration). This map is resampled to match the 600 pixel array of the BrainPort IOD and presented as intensity (a tingling sensation) on the tongue. With a few minutes of training, a user can learn to interpret this signal as pressure on his or her feet.

Similarly, joint position from the actuator encoders and torque estimated from actuator current draw can be used to estimate the position of the Mina-user system CG over

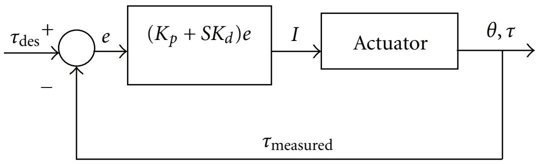


Figure 4: Diagram showing the feedback loop used to control the output torque of the actuator.

the stability polygon defined by the current stance as well as the relative "effort" exerted by Mina to maintain the current posture or execute a step. When presented on the VideoTact as a moving CG icon and a dynamic stability polygon, we believe that users will be able to effectively maintain awareness of their limits of stability during ambulation.

3. Gait Generation and Operation

Mina operates as a motion capture system that records trajectories from an able-bodied individual, which can then be "played back" in the paraplegic assistance mode. This method allows for generation of a natural gait with a quick development cycle.

3.1. Generating Walking Trajectories. Walking trajectories were generated from joint position recordings made while an able-bodied person wearing Mina walked over level terrain in the laboratory. This method of gait trajectory generation was selected because it allows for relatively natural gaits and the ability to develop new gaits in a short period of time. During this process, the actuators were set to torque control mode. For the hip joints, the desired torque was set to zero so that Mina would follow the user's motions without affecting them. Compliance in the user's flesh and the braces of Mina can result in a few degrees of offset between the user's joints and the device's joints. For example, full knee extension may occur before the knee joint of Mina extends fully. However, in paraplegic assistance mode, stable stance requires that the Mina knee joint extend fully. In order to assist the knee joint to the fully extended position while recording the gait, the desired torque was set to be 10 Nm in extension. This torque, generated by the actuators, ensured that the knee was fully extended during stance phase while allowing the able-bodied user to overcome it during swing.

Toe-off provides a significant component of natural gait [28] and people minimize the ground clearance of the foot as part of a muscle energy conservation strategy. However, for a robotic orthosis, electrical energy conservation does not equal muscle energy conservation. Because Mina lacks an ankle actuator, the able-bodied user walked with an exaggerated ground clearance in swing phase during gait recording to guarantee that the toe does not stub on the ground. The resulting gait mimicked walking on a slippery surface (i.e., with minimal the ground reaction shear forces). Because Mina does not have the same actuated degrees of freedom as a healthy person, the resultant gait cannot match that of a healthy person. In human walking, there is complex feedback loop between terrain sensing, joint position, and body position. Replicating this complex loop, especially the terrain sensing, will be studied in future work.

Table 1

Leg length (dist. from hip joint to ankle)	Actual step size	Step period	Walking speed
0.840 m	0.24 m	1.4 s	0.18 m/s
0.785 m	0.28 m	1.4 s	0.20 m/s

After the recording phase, the trajectories were played back in paraplegic assistance mode with an able-bodied user with relaxed lower limb muscles. From this playback, the best single gait cycle (stance and swing phase) was selected to use as a basis for the final walk. The joint angles at the end of this gait cycle were adjusted to match the starting joint angles, allowing the step to be played back in a smooth, endless loop. The joint angles were then copied to the other leg with a half cycle phase shift. This ensured that the left leg and the right leg executed the exact same step with the appropriate phase shift.

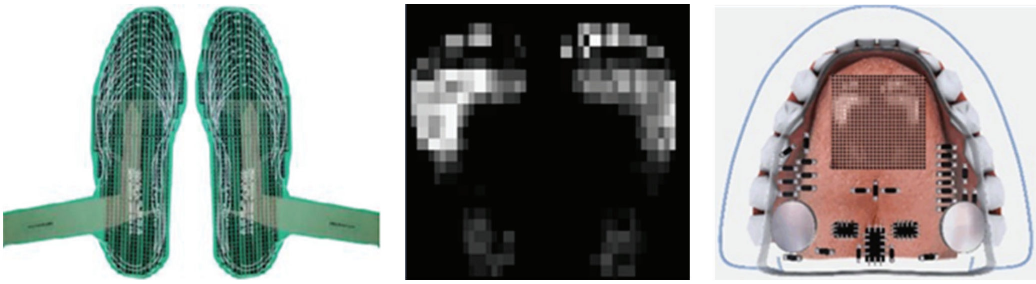
Three different walks were recorded, with step sizes ranging from zero (stepping in place) to what will be referred to as a large step. The precise value of the step size for a given walk depends on the leg length of the user. The quickest step period we have used to date with Mina is 1.4 seconds per step. The resulting walking speeds are presented in Table 1. Note that the recorded gait consists of a sequence of desired joint angles. The resulting walking speed is a function of how fast this sequence of desired joint angles is played and of the leg length of the user. The longer the user leg length the larger the actual step, and thus the faster the resulting walking speed. The fastest walk speed recorded was 0.2 m/s (see Table 1), which was limited by actuator performance rather than user capability.

The joint angles at the end of the best single recorded gait cycle (stance and swing phase) were adjusted to match the starting joint angles, allowing the step to be played back in a smooth, endless loop, and the joint angles were then copied to the other leg with a half cycle phase shift.

3.2. Operation. The Mina currently requires an external control operator in paraplegic assistance mode to activate/deactivate the system, trigger a single step or continuous steps, stop walking, and change gait speed between 50% and 130% of the recorded speed. In addition, the operator can adjust the time the controller pauses between left and right steps and responds to verbal and gesture cues from the user. For effective real-world mobility assistance, the user must have full control of the exoskeleton, which requires sensory perception of the orthosis dynamics. Sensory substitution interfaces provide this functionality in the updated Mina device.

4. Results from Initial Evaluations

Following IHMC Institutional Review Board (IRB) approval, two evaluators tested the initial Mina prototype. We required the evaluators to have an American Spinal Injury Association



(a) (b) (c)

Figure 5: (a) Insole pressure sensory arrays (F-Scan); (b) visual representation of ground reaction force; (c) Mina representation of contact forces on Wicab BrainPort IOD.

(ASIA) Impairment Scale [29]. A (Complete) and a Walking Index for Spinal Cord Injury (WISCI) level 9 (Ambulates with walker, with braces and no physical assistance, 10 m) or higher [30]. Although the evaluators were able to walk prior to their SCI, walking in Mina differs significantly from able-bodied walking. As mentioned before, complete paraplegics lack feedback of the ground reaction force and center of pressure on their feet. Additionally, they do not use their remaining proprioception feedback loop for balance as frequently as able-bodied persons because they spend most of their awake hours seated. Finally, when walking in Mina, their arms become an integral part of balance and ambulation as they ambulate with a quadrupedal crawl consisting of a hind foot, ipsilateral front crutch, contralateral hind foot, and contralateral front crutch sequence. Because of the lack of integrated sensory feedback in the initial prototype, we placed a video monitor in front of the evaluator during initial training, which provided a real-time side view but forced the user to choose between watching the monitor and watching his or her legs directly. The user must learn how to position his or her body at the point of heel strike. If the user leans too far backward, then the upcoming swing leg will still be loaded at the time of swing, causing a backward fall. If the user leans too far forward, the foot will contact the ground before the swing completes, resulting in significantly reduced step size. Large step sizes with this prototype often caused the evaluator's center of mass to remain between the two feet during double support, leaving the trailing leg loaded as it initiated the next swing phase and triggering a fall. Using smaller steps mitigates this problem; however, this accentuates the need to provide appropriate sensory feedback for a more dynamic gait that could control a passively (spring loaded) or actively actuated ankle for toe-off. While both evaluators could easily walk with forearm crutches (Figure 6) as a quadruped with low cognitive effort [31], we believe that the next iterations with sensory augmentation will result in a more upright gait.

5. Discussion

We evaluated Mina with two paraplegic evaluators and demonstrated that Mina is currently capable of providing mobility for paraplegic users on flat ground at slow walking speed. Even though Mina currently operates in a high impedance trajectory-tracking mode, able-bodied users tend to actively try to walk and balance using sensory feedback, such as ground reaction forces. The addition of sensory substitution interfaces to Mina will allow paraplegic users to receive similar information and should allow similar control behaviors. In evaluating Mina, we observed that all users required some amount of training and practice and that more training and practice was required for paraplegic users than able-bodied users. As with any new activity that requires coordinated motion, proficiency requires practice. The addition of proprioception analogs for the lower extremities in paraplegic users should reduce the cognitive effort and time to learn the task of coordinating arm motion with leg motion.

Figure 6: The Mina during evaluation.

6. Future Work

Feedback systems integrated to Mina will seek to convey sensory information related to these characteristics of human balance during stance and dynamic gait. IHMC is evaluating the effects on balance of various tactile display symbologies by determining the *user's control stability* (maintenance of his or her balance and the deviation of his/her center of mass) as well as the *user's perception* accuracy by asking him or her to estimate how much he/she deviates from a desired body posture. It will also be interesting to measure the participants' accuracy to estimate their body deviation when using the tactile feedback. These subjective estimations will guide design of the sensory feedback system and the symbology needed for user control of the Mina hardware. We are incorporating a video game interface using a WiiFit balance board (Nintendo Co, Ltd., Kyoto, Japan) as a stability measurement device for static posture with and without sensory substitution feedback and forearm crutches. The game element improved participant engagement as they learn to control their balance [32]. The data analysis will guide improvements that will ultimately lead to direct, dynamic control of Mina by the user. Lastly, we are integrating functional electrical stimulation (FES) to manage toe-off and toe-lift to allow Mina to use less exaggerated gait trajectories.

7. Conclusions

In this paper we introduced the Mina exoskeleton concept that can play back prerecorded joint trajectories using compliant control rather than rigid joint trajectory tracking to allow for robustness to unmodeled terrain variations and perturbation. Two device evaluators with spinal cord injury paraplegia maintained balance with forearm crutches to walk with a quadrupedal gait. This demonstrated the need to integrate sensory feedback systems with powered actuator mobility assistance robotics even for walking at relatively low speed on flat ground in a laboratory setting. We are currently developing various improvements to give the user operational control of the device using gestures provided by upper body motion. We will also investigate tracking user gaze as a control mechanism when navigating complex environments to, for example, adjust step height and step plant when walking on rough ground. Further development will continue to reestablish the sensorimotor loop by restoring sensory feedback and will improve user/orthosis coupling to form an integral sociotechnical team. This should enable increasing the speed of walking, walking over rough terrain, on hiking trails, and in urban environments with stairs and narrow passageways as well as a more natural upright, assisted bipedal gait.

Conflict of Interests

The authors have no financial conflicts of interest with respect to the work described. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Office of Naval Research.

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