Design and Experimental Evaluation of a Vertical Lift Walker for Sit-to-Stand Transition Assistance

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A walker capable of providing vertical lift support can improve independence and increase mobility of individuals living with spinal cord injury (SCI). Using a novel lifting mechanism, a walker has been designed to provide sit-to-stand assistance to individuals with partially paralyzed lower extremity muscles. The design was verified through experiments with one individual with SCI. The results show the walker is capable of reducing the force demands on the upper and lower extremity muscles during sit-to-stand transition compared to standard walkers. The walker does not require electrical power and no grip force or harness is necessary during sit-to-stand operation, enabling its use by individuals with limited hand function. The design concept can be extended to aid other populations with lower extremity weakness.
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1 Introduction

The capability to rise from a seated to standing posture is critical to independence and mobility. Sit-to-stand transition is one of the most physically demanding maneuvers for the muscles of the lower extremity, and therefore, one of the largest obstacles to independence for those with lower extremity muscle weakness. Often times, such individuals become dependent on the use of their upper extremities and a mobility aid, such as a walker, to rise from the seated position. The sit-to-stand challenge can be further exacerbated when the upper extremities are unable to provide the necessary support during sit-to-stand; such situations are common in the aging and overweight population. The sit-to-stand transition is also problematic after a traumatic injury, such as spinal cord injury (SCI), which results in weakness or paralysis of the upper extremity in combination with the lower extremities. Consequently, the sit-to-stand task is the subject of intense focus during rehabilitation [1,2].

Functional neuromuscular stimulation (FNS) is an intervention which can restore motor function to paralyzed muscles thorough the use of electrical stimulation. FNS systems have been implemented to restore standing to individuals with lower extremity paralysis [3–7]. These systems are successful in paraplegic subjects; however, they require significant upper extremity force for stabilization both during the dynamic ascent and static standing. Other research has focused on the development of robotic [8–14] systems which aim to restore independent sit-to-stand function. These devices utilize motors or linear actuators to assist individuals in sit-to-stand transition, resulting in assistive devices which are much bulkier than standard walkers. Furthermore, many robotic assistance systems are not intended to serve as walking aides, and thus require the user to employ a second device for gait. Finally, robotic interventions also result in horizontal movement of the torso during ascent which requires grip force from the user, or the use of harnesses or strap to compensate if grip force is diminished. A third class of assistive devices termed passive sit-to-stand assistance devices have been developed [15]; however, such systems are bulky and do not easily allow for transition or assistance with walking.

In the absence of neuroprosthetic or robotic interventions, many individuals are relegated to assistance from others to move from the seated to standing position. To enhance independence, a new class of devices called lift assist walkers have emerged, resulting in several commercially available products and patented designs [16–19]. Most lift assist walkers incorporate gas springs in the lift assist application. These springs contain gas in a sealed cylinder which is compressed or expanded by a moving piston. Because the gas in the springs is pre-compressed, these devices provide consistently large force output through the entire range of motion. Commercially available walkers typically mount gas springs in a linkage mechanism which rotates a handle or platform around a stationary point to provide lift assistance [11,12]; the resulting motion moves the platform forward, away from the user, as it moves upward. As a result, these devices require the user to grip the walker platform during sit-to-stand transition, a capability many people living with paralysis do not possess. Some commercially available walkers offer a harness worn around the pelvic region to counteract this effect; however, this creates donning/doffing and comfort issues. One currently available walker provides vertical platform motion, but a battery is used during operation [14].

The objective of this work was to design a simple, effective, non-electrically powered sit-to-stand assistance device for use with an implanted functional neuromuscular stimulation (FNS) system to facilitate standing and walking function after motor incomplete SCI. Users of implanted stimulation systems for walking often have difficulty rising from the seated position without assistance because stimulated lower extremity muscles do not create sufficient vertical force. In some cases, the upper extremities can be used to ease force requirements on the legs; however, this is problematic for many with SCI who also suffer from upper extremity weakness. To address the needs of these individuals, we propose a new vertical lift walker which can provide sit-to-stand assistance and then be used intuitively as a mobility aid during walking with the FNS system. The device must support the user's full body weight at any position in the event that the stimulation system is turned off. Finally, the walker should safely return the user to the seated position.

To achieve the above performance specifications, gas springs are implemented in a different way to create a power-free lift assist walker with purely vertical platform motion. Such operation is advantageous to the spinal cord injury population which lacks hand function to grip handles or bars to maintain coupling with a walker platform.

The lift force and range of motion for the prototype walker were customized for one individual. The full set of design specifications can be found in Table 1. The prototype walker design is unique in that it does not require any electrical power, and provides vertical lift assistance without requiring the user to exert grip force or wear a harness. Operation of the walker will proceed as follows. When standing is desired, the user will depress a single button to activate the gas springs, which will provide assistive force in the vertical direction. Note that the assistive force is designed to be less than is needed for the full sit-to-stand transition; thus some lower extremity force, provided by electrical stimulation, is required. Once standing has been achieved, the button

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Table 1 Vertical Lift Assist Walker Design Specifications

Criteria	Values	Units
Vertical lift force	890/200	N/lbf
Weight support capacity	1335/300	N/lbf
Minimum platform height from floor	0.85/34	m/in
Maximum platform height from floor	1.35/54	m/in
Vertical range of motion	0.50/20	m/in
Width (inner frame)	0.80/32	m/in
Depth (front to back)	1.00/40	m/in
No anterior-posterior or medial lateral platform motion	–	–

is released and the walker platform locks in the vertical direction. The user can then utilize the walker for mobility assistance while walking with the FES system. When desired, the user can return to a seated position by turning off the electrical stimulation and then pressing the button to unlock the gas springs; the walker platform will lower the user back to the seated position using body weight to overcome the force from the springs.

2 Methods

2.1 Design and Fabrication. In addition to the above specifications, the following requirements dictated the design and component selection for the prototype lift walker: (1) mobility requirements demanded that all components be as lightweight and compact as possible, (2) portability and transportation issues required the walker to be modular such that it could be assembled/disassembled easily, and (3) to minimize cost and complexity, commercially available components were employed when possible. Owing to the shortcomings of currently available lift assist walkers, the design of the current prototype provides lift assistance for the sit-to-stand transition through purely vertical motion (Fig. 1). The user interface is a standard, widely available platform commonly found on walkers with manual height adjustment. Such platforms allow users without hand grasp capabilities to walk by placing their forearms on the platform and supporting body weight through the shoulders. This platform will move relative to the walker frame through extension/compression of bilateral gas springs.

The base for the prototype lift walker is the well known, four-legged walker with casters on the front two legs and friction resistant caps on the rear. This frame is similar to standard walkers, which are stable and mobile, but provide no lift assistance. To minimize weight and enhance modularity, the base was constructed from 1 in. outer diameter aluminum piping with a 0.113 in wall thickness connected by structural fittings. Adjacent pipe sections were placed in the fittings – elbows or tees – and secured using set screws tightened on flattened sections of pipe.

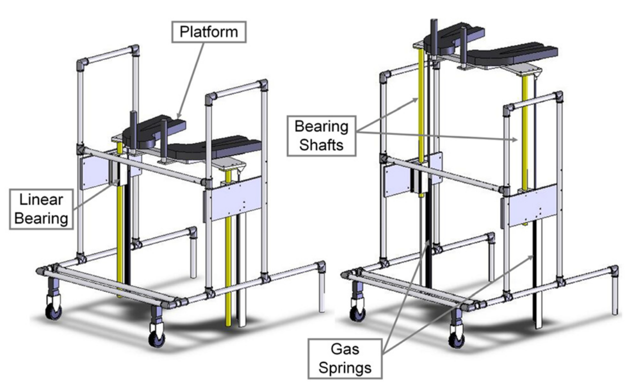

Fig. 1 Design concept of the vertical lift assist walker. The platform moves vertically and provides a vertical lift force equal to roughly 80% of body weight. Lift force is provided through bilateral gas springs. Platform motion is guided by self aligning linear bearings, which prevent tilt and hold the platform horizontal.

A novel pneumatic elevator assembly was designed to lift the platform (Fig. 2). Commercially available, remote release gas springs (Bansbach Easylift, Melbourne, FL) with a 20 in range of motion were chosen as the actuators for the lifting mechanism. The gas springs provide approximately 100 lbf at full compression and 90 lbf at full extension, with a linear force profile between these points. Each spring contains a locking valve controlled by a hydraulically actuated pin within the rod end; when the pin is released (the button is pushed) the rod end is free to move. When the pin is engaged, the gas springs are locked at their current position. The pin within the rod-end can sustain up to 1300 N of force in the locked state. The springs are biased into full extension such that when the pin is released, a force of approximately 100 lbf is required to compress the spring.

Two gas spring actuators were attached bilaterally to create the pneumatic elevator assembly. The gas springs were rigidly connected to the platform using standard clevis-pin assemblies mounted to custom designed aluminum plates (Fig. 2(*c*)). To achieve the desired range of motion, custom brackets were designed to offset the bottom cylinder mount point. These brackets also shield the user from the moving parts of the gas springs. The bottom mount of the cylinders consists of a ball-joint fitting with a socket on the cylinder and a ball-stud to connect the socket to the bracket (Fig. 2(*d*)). This universal style connector permits 360° of rotation to compensate for load misalignment.

The walker must be able to support the body weight of the user in a locked state. A finite element analysis of the stress was conducted under for a total walker load of 1335 N (300 lbf), or a load of 667 N (150 lbf) per spring, to assure that a single ball-stud could withstand the shear stress of the user weight. The results (Fig. 3) indicate the bolts can support the cylinders with a safety factor of approximately 1.53.

Vertical motion of the bilateral springs is coupled through a single hydraulic push button release system, allowing the release of both springs with the push of one button. The gas springs are configured so they lock in place at all times when the push button is not compressed. In the locked state the spring assemblies are able to support in excess of 1335 N (300 lbf) as described above. When desired, the user pushes the release button and the gas springs extend to provide a vertical lift force of approximately 890 N (200 lbf) for sit-to-stand assistance. Once upright, the button is released to lock the springs. To sit, the user simply pushes the button and uses body weight to compress the cylinders.

Bilateral linear ball bearings and case-hardened precision steel shafts (McMaster-Carr, Santa Fe Springs, CA) were employed to achieve relative vertical motion between the platform and the walker frame. The linear ball bearings, which can accommodate up to 1° of shaft misalignment, are mounted in an aluminum pillow block. The shafts are coupled to the motion of the linear springs and platform through the custom designed platform brackets. The lift mechanism is connected to the walker frame using two mounting plates. The mounting plates are multi-functional. They serve as a mounting surface for the bearing blocks while providing mounting for the cylinder brackets and stabilizing the four legged walker base to the high dynamic loads experienced during weight support. In total, three custom designed and fabricated components are used in the lift assist walker. These parts allow for the precise placement of the lifting mechanism attachment points on the frame, enabling the platform to move vertically through the specified range of motion.

2.2 Experimental Verification. Once constructed, the prototype lift walker was tested on three able bodied subjects (mass $= 85.3 \pm 15.8$ kg) to verify the design and assure the walker could safely lift and support the specified loads. During these tests, the subjects used the lift walker to transition from a seated

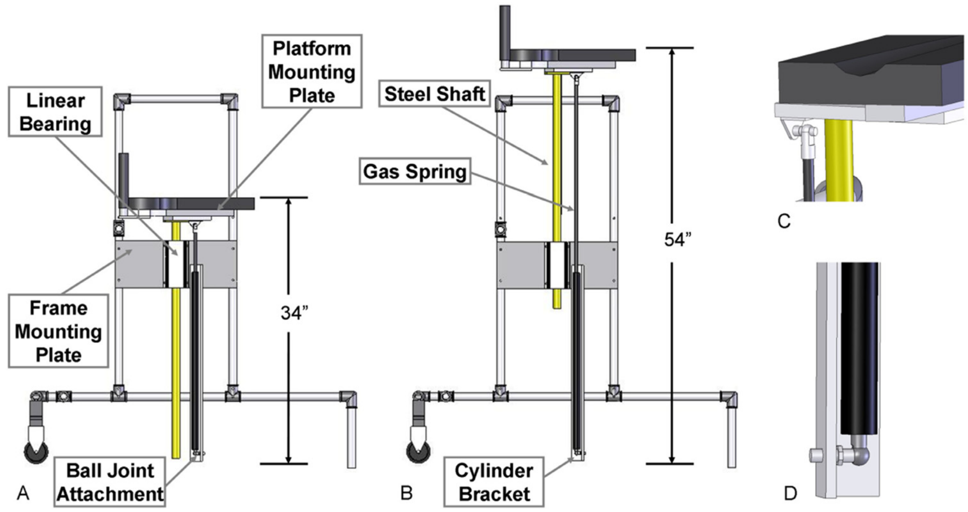

Fig. 2 Pneumatic elevator components. The gas springs actuate the assembly. (*a*) The platform sits 34 inches from the ground in the fully compressed position. (*b*) In the fully extended position, the platform height is 54 inches. (*c*) Clevis-pin rod end attachment of gas spring to walker platform. (*d*) Ball-joint rod end attachment of gas spring cylinder to mounting bracket.

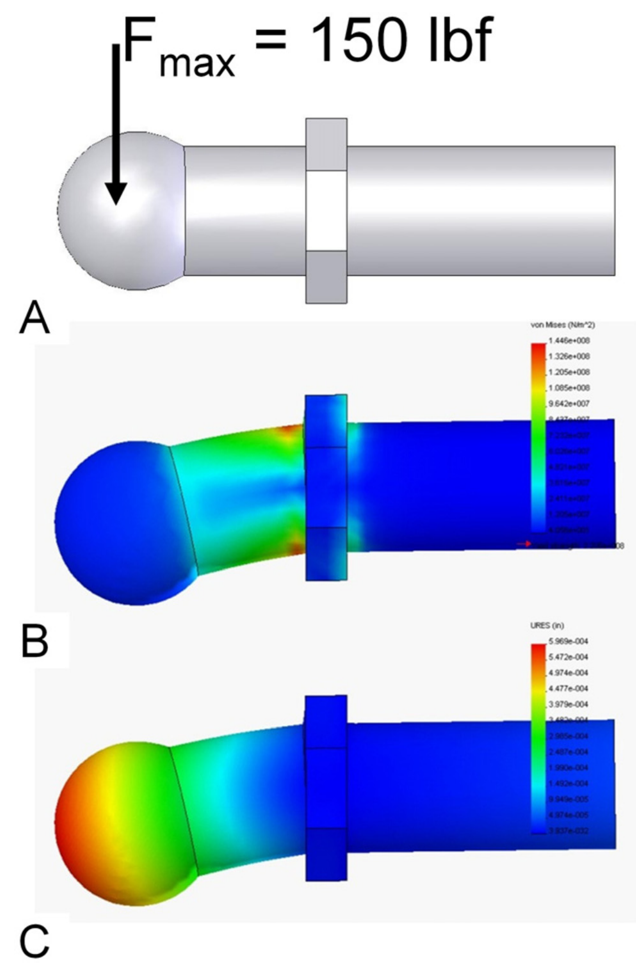

Fig. 3 Finite element stress analysis of the ball-headed bolt which connects the gas springs to the walker. (*a*) The maximum applied load depicted on a solid model of the bolt, made from plain carbon steel (yield strength of 2.2×10^{-8} N/m^2). (*b*) Stress distribution under maximum load. Maximum stress was approximately 65% of yield stress. (*c*) Displacement of the bolt during maximum loading. Maximum displacement was 6.0×10^{-4} inches.

to standing posture. The subjects also loaded the walker with their full body weight in the standing position by removing their legs from the floor with their arms on the platform.

After the design and safety of the walker was verified in able bodied subjects, one subject with incomplete spinal cord injury (SCI) was recruited to test the ability of the walker to assist in sit-to-stand transition. The male volunteer (age 40, six years post injury, mass = 64.5 kg) with motor incomplete SCI (C6/7 level, ASIA D) was able to rise from a seated to standing posture on his own through the use of his upper extremities on a walker. Experiments were performed to compare the prototype lift walker with a standard walker during the sit-to-stand transition.

In all experiments, a Vicon® MX40 motion capture system (Vicon Motion Systems, Oxford, UK) was used to track the lower and upper extremity kinematics of the subject, as well as the kinematics of the lift walker. During sit-to-stand transition, the vertical motion of the torso was monitored as the motion of the plane defined by four markers placed on the right shoulder, left shoulder, seventh cervical vertebra, and the clavicular notch. Force plates (AMTI, Watertown, MA) under each foot were used to measure lower extremity force data. The standard walker was outfitted with two load cells (AMTI, Watertown, MA) mounted below the handles of the walker to measure upper extremity lift force. The vertical lift force provided by the prototype walker was computed using inverse dynamics from the measured kinematics and lower extremity forces.

All data were sampled at 100 Hz and filtered offline with a third order, low pass, digital Butterworth filter with a cutoff frequency of 5 Hz. Five trials of sit-to-stand transition were performed under each experimental condition. An analysis of variance (ANOVA) was used to compare measured quantities across experimental conditions, with $p < 0.05$ considered significant.

3 Results

3.1 Fabrication. A prototype walker was constructed and tested on both able body and spinal cord injury test subjects (Fig. 4). The total walker cost, including machining, was $1,658, which is equal to or less than the cost of currently available lift walkers. The base frame of the walker is 0.80 m (32 in) wide and 1.0 m (40 in) deep. This foot print easily enables a user to position a standard wheelchair adjacent to the platform (Fig. 4).

As constructed, the platform moves through a 0.50 m (20 in) range of motion, starting at fully retracted position of 0.85 m

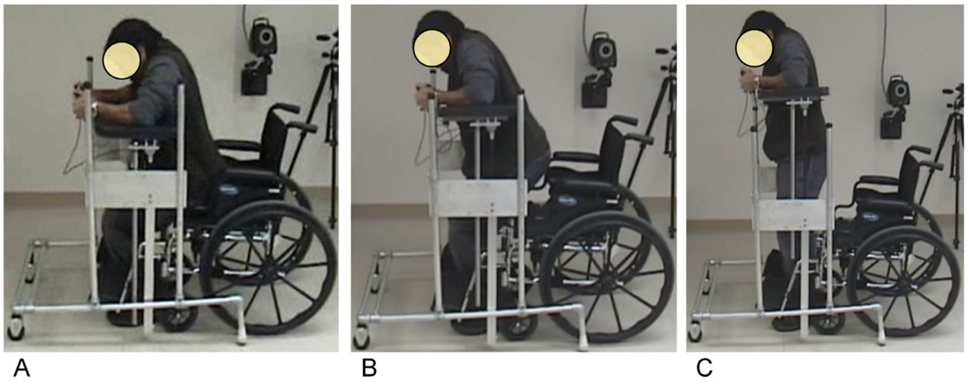

Fig. 4 Photographs of a sit-to-stand transition using the prototype lift assist walker. (*a*) Initially, the walker is locked in the seated position. (*b*) Upon pressing the release button, the gas springs exert 890 N (200 lbf) of force through the shoulders of the user to lift him from the chair. (*c*) The walker is locked in the fully extended position, capable of supporting loads in excess of 1335 N (300 lbf).

(34 in) from the ground, and finishing at a fully extended height of 1.35 m (54 in). When the hydraulic release button is pressed, the gas springs exert vertical force on the platform in the upward direction to assist the user in the sit-to-stand transition. When the hydraulic release button is not engaged, the walker is locked to support body weight. The walker can be locked at any position within its range of motion. The walker is compressed back to the seated position by pressing the release button and applying body weight greater than the supplied force.

3.2 Experimental Evaluation. The ability of the prototype lift walker to assist in sit-to-stand transition was examined during experiments with one SCI subject under two conditions: using a standard walker (control) and using the prototype lift walker (experimental). The duration of the sit-to-stand transition was significantly longer with the control walker ($p < 0.0000$), with the average sit-to-stand transition taking 3.79 s compared to 2.30 s for the lift walker. Because of this time difference, and for comparison purposes, the sit-to-stand transition under each condition was normalized in time into cycles ranging from 0–100%. The lift cycle was then expanded by 10% at the beginning and end of the sit-to-stand transition to assure the beginning and end of the maneuver was captured.

Sit-to-stand transition using the vertical lift walker resulted in a steadier, more consistent rise than with the control walker (Fig. 5). Using the standard walker, there is a drastic increase in upper extremity position and velocity between 15%–40% of the lift cycle. This is accompanied by a rise in lower and upper extremity vertical force (Fig. 6 and Fig. 7). Between 40–60% of the lift cycle, the velocity of the torso decreases as does the force supplied by the upper extremities, while the leg force remains nearly constant. In the last 40% of the cycle, the torso velocity is nearly zero as the weight is transferred from the upper extremities to the legs. Using the standard walker, the mean maximum upper extremity force provided by the user was 473.9 ± 3.9 N (106.5 ± 0.90 lbf) and the mean maximum leg lifting force was 715.1 ± 25.5 N (160.8 ± 5.7 lbf). Thus, substantial user effort is evident during sit-to-stand transition with a standard walker.

Using the prototype lift walker, torso motion is observed to be significantly steadier during the rise to the standing position (Fig. 5). The force from the gas springs results in a nearly constant torso velocity during the sit-to-stand transition. Lifting force required from the legs is significantly reduced (Fig. 6, $p < 0.0000$) compared to the standard walker with a mean maximum of

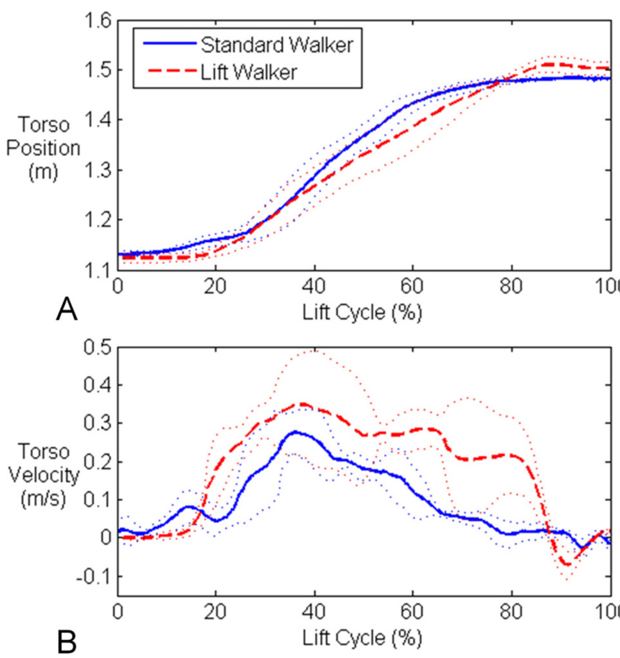

Fig. 5 The mean vertical torso position (*a*) and mean velocity (*b*) during the sit-to-stand transition, normalized in time by the lift cycle. Position is relative to the ground. The dotted lines are ±1 standard deviation.

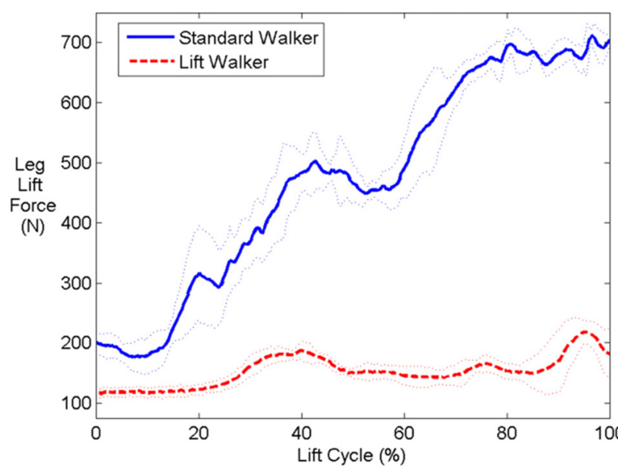

Fig. 6 The mean lower extremity lift force exerted by the user during the sit-to-stand transition with a standard walker and prototype lift walker. The dotted lines are ±1 standard deviation.

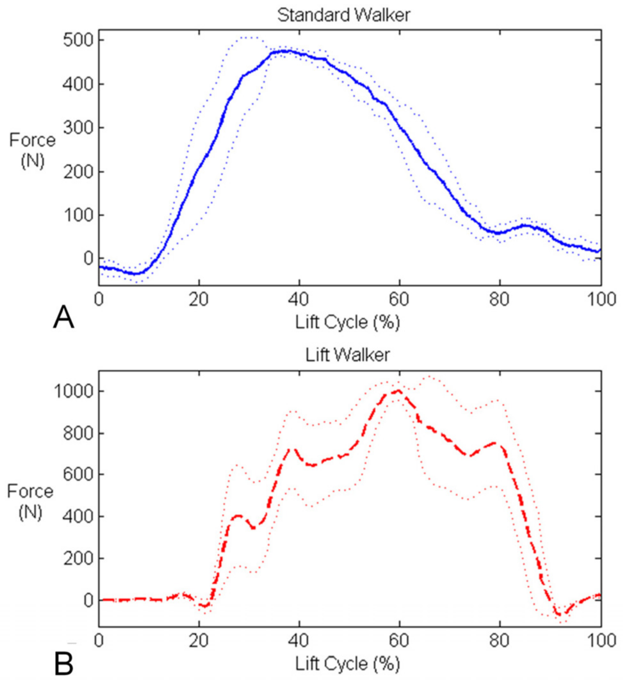

Fig. 7 (*a*) The mean upper extremity vertical force exerted by the user during sit-to-stand transition with a standard walker. (*b*) The mean lift force exerted by the prototype lift walker during sit-to-stand transition. The dotted lines are ±1 standard deviation.

224 ± 24.3 N (50.4 ± 5.5 lbf). The upper extremity force observed during sit-to-stand with the standard walker is replaced by the force supplied by the lift walker (Fig. 7(*b*)). In essence, the user rides the platform in the vertical direction rather than exerting effort to rise to the standing position. The mean maximum lift walker force was 1037.5 ± 40.8 N (233.3 ± 9.2 lbf). Thus, the lift walker eliminates the need for the user to supply vertical force using their muscles, and instead, provides assistive force on command.

4 Discussion

These preliminary testing data indicate that the prototype lift assist walker is able to successfully reduce the required leg and upper extremity lift forces during the sit-to-stand transition. The prototype lift assist walker results in a faster, more consistent rise trajectory than with a standard walker.

The lift force and range of motion achieved by the prototype walker presented in this paper have been customized for one individual. Since gas springs are available in a wide range of sizes and forces, the concept can be applied to nearly any sit-to-stand lift assist application by changing the design of the custom mounting brackets. One shortcoming of the current design is the maximum lift force provided by the springs must be less than the body weight of the user to allow spring compression during stand-to-sit transition. Thus, some volitional (or electrically stimulated) lower extremity muscle function is required to achieve standing. The concept could be extended for use in individuals with a motor complete injury without a functional electrical stimulation system through incorporation of a second set of gas springs to counteract the lifting force. Activation of these springs simultaneously with the lifting springs cancels their lift force, allowing the platform to return to the seated position under the load of user weight.

The vertical lift assist walker is novel because it provides purely vertical motion of the platform, nearly constant upward force throughout the entire range of motion, and does not require any electric power. The vertical motion of the walker platform minimizes hand grip force required during the sit-to-stand transition, enabling its use by individuals with weak upper extremities. This device was designed to assist people with incomplete SCI move from the seated to standing position for walking with electrical stimulation. However, the design itself is universal, and could assist other populations with limited mobility due to weight issues or diminished lower extremity strength and motor control, including individuals recovering from surgery, suffering from lower extremity muscle weakness as a result of stroke, neurologic disease, or aging.

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