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6 **Biomechanical validation of upper extremity exercise in wheelchair users: design**
7 **considerations and improvements in a prototype device**
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9 *Disability and Rehabilitation: Assistive Technology*
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11 Accepted for publication: July, 2010
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32 **Abstract:**

Purpose: To develop guidelines for proper exercise execution on a novel device and to recommend design changes to the device based on biomechanical data and user feedback.

Method: Seven manual wheelchair users were instructed on proper exercise technique with a novel device, which allows a person to complete a seated row. Kinematics and kinetics of the dominant upper limb and trunk were measured with motion capture and electromyography data were collected on select muscles.

Results: All subjects were able to exercise on the device with a mean power of 21.3 W (SD 7.1 W). Subjects did not keep the elbows close to the trunk during the drive phase of the row; rather, they moved from mean 75° (SD 12°) shoulder flexion to mean 62° (SD 11°) shoulder abduction. Identified problems included difficulty gripping the hand grips and user stability within the wheelchair.

Conclusions: The accessory unit should be adjustable to accommodate a wide range of user sizes and abilities. Proper exercise execution is important to maximize the potential benefit and minimize risk of injury. When executed properly, this exercise may benefit wheelchair users by improving cardiovascular fitness and strengthening muscle groups linked to the reduction of shoulder pain.

Keywords: upper extremity; wheelchair; shoulder pain; exercise; universal design

Introduction

The functional consequences of lower-limb disability include diminished independence, fitness, work capacity and recreational/employment opportunities [1,2]. Additionally, shoulder pain is a major secondary condition experienced by manual wheelchair users [3], and can adversely affect physical performance, participation in major life activities, and overall quality of life in this population. Over time, independently propelling a manual wheelchair and performing frequent transfers results in repetitive motion injuries at the shoulder, elbow, or wrist [4]. These motions rely heavily on use of the anterior shoulder muscles and the resulting muscle imbalance may contribute to injury [5]. Chronic conditions such as carpal tunnel syndrome, rotator cuff injuries, elbow/shoulder tendonitis and bursitis, and osteoarthritis have also been associated with long-term manual wheelchair use [6,7]. Identifying methods for reducing shoulder pain and injury among manual wheelchair users is an important area for research. Regular exercise has been linked to a reduction in shoulder pain and an improvement in cardiovascular fitness in manual wheelchair users [8]. Exercise that targets posterior shoulder muscles may be especially beneficial in this population because of its potential to improve muscle balance [9]. Improved fitness and reduced pain both contribute to this population's continued independence.

While there are upper-body cardiovascular exercise machines available (i.e., arm ergometers), they typically are not part of the regular complement of exercise equipment found at community recreation and fitness facilities. The economic realities of producing specialized equipment for a currently small market segment make these devices relatively costly. The additional floor space required for this equipment is often at a premium in many community fitness centers, private homes and apartment dwellings [10]. At the same time, the lack of accessible exercise machines makes joining a health and fitness center less attractive to people

with disabilities, thus completing a vicious circle. Furthermore, several studies have reported that arm ergometry and wheelchair ergometry often precipitate upper extremity injuries that compromise a wheelchair user's ability to perform various activities of daily living [1,11,12]. These concerns have challenged investigators to find alternative exercises for improving cardiovascular fitness [8,13].

In this context, a universally designed accessory unit was developed to include upper-body exercise in existing Life Fitness cardiovascular equipment (9500HR stationary cycle; Life Fitness Inc., Schiller Park, IL, USA). As shown in figure 1, a wheelchair user can easily approach the accessible cycle from the front and grasp a single straight handlebar with both hands to complete a seated rowing motion. The stationary cycle continues to function normally for able-bodied users. For an able-bodied user on a commercial rowing ergometer or in a rowing shell, the drive (force-producing) phase of rowing involves coordinated extension of the knees, hips, trunk, and shoulders, and flexion of the elbows [14,15]. Because most individuals in wheelchairs have limited use of the lower extremities, the present exercise emphasizes motion of the shoulders and elbows. Depending on the disability, users may also engage muscles controlling the trunk during this exercise.

insert figure 1 here

Our purpose was to develop guidelines for proper exercise execution and recommend design changes to the accessory unit based on biomechanical data and user feedback. To accomplish this we analyzed upper extremity kinematics, kinetics, and electromyography (EMG) of manual wheelchair users as they exercised on the modified stationary cycle. We expected the upper extremity motion of subjects to primarily consist of shoulder extension and elbow flexion during the force generating portion of the exercise, along with activation of the posterior deltoid,

biceps, and latissimus dorsi. The data were used to (1) identify and address problems identified by disabled subjects using the equipment, (2) quantify the external forces upon and muscle activation within the upper body during exercise to develop guidelines for proper exercise execution, and (3) verify that exercise kinematics were not potentially injurious.

Methods

Seven manual wheelchair users (4 females, age: 22-50 years, height: 155-178 cm, mass: 50-73 kg) volunteered to participate in this institutionally reviewed and approved study. All participants gave written informed consent before data were collected. Inclusion criteria included being in good health, using a manual wheelchair as a primary means of mobility and the ability to grip with the hands. Exclusion factors included upper extremity or back injury, diabetes, cardiovascular or pulmonary disease, the use of medications that might affect balance or strength, and a spinal cord injury at T1 or above. None of the subjects had any experience with rowing prior to their participation in the research. Reasons for wheelchair use were diverse and the study population included subjects with spinal cord injuries, sympathetic reflex dystrophy, multiple sclerosis, and several other conditions. Notably, some subjects had full use of their upper body and trunk, while others had more systemic disabilities.

Subjects were positioned in front of the equipment with their arms comfortably extended in front of them so that the handle-bar was fully retracted and would immediately resist any pulling by the subject. The starting position is shown in figure 1. Each subject sat in his or her own wheelchair with the wheels locked in place or with blocks in front of and behind the wheels for those subjects who did not have brakes on the chair. After a demonstration of proper exercise technique and 15-30 repetitions to practice using the equipment, subjects each performed three bouts of 20 exercise cycles (i.e., 20 pulls of the handle bar) at a self-selected intensity. Subjects

were encouraged to exercise “as if they were trying to get a work-out” and were offered a rest period between exercise bouts to avoid fatigue. Each bout of exercise was self-initiated by the subject and data collection was started after a constant intensity was reached, which took 3-5 cycles.

The motions of the trunk and dominant upper extremity were measured using 11 passive reflecting markers used to make a 4-segment model (trunk, upper arm, lower arm, and hand;[16]. This marker set allowed quantitation of shoulder plane of elevation (indicating flexion at 90°, abduction at 0° and extension at -90°), shoulder angle of elevation, humeral internal/external rotation (with 0° when the elbow axis was aligned mediolaterally), elbow flexion/extension, wrist flexion/extension and radial/ulnar deviation. All kinematic data were processed and described in accordance with ISB standards [17] using custom written software (Matlab, The Mathworks, Natick, MA, USA). An 8-camera motion capture system (Motion Analysis, Santa Rosa, CA, USA) was used to collect kinematic data at 60 Hz. A load cell was placed in series with the handles to record pulling forces at 1200 Hz.

Electromyography (EMG) was used to determine muscle onset times and duration of activation during exercise. One-cm diameter dipole surface electrodes (Noraxon Inc., Scottsdale, AZ, USA) were placed over subjects’ anterior and posterior deltoid, biceps, triceps, trapezius, and latissimus dorsi on the dominant side. Data were collected at 1200 Hz, zeroed, high-pass filtered with a cutoff frequency of 200 Hz to remove any low-frequency motion artifacts from the data, and rectified. Muscle activation was defined as any activation greater than 1 standard deviation above resting and at least 50 ms in duration [18].

For each subject, the data from each cycle were normalized to 100 data points, representing 1-100% of a complete cycle. For kinematic variables, mean data were generated for

each subject and were combined to generate a group mean. For EMG, muscles were either considered active or inactive at any given point during a cycle, based on the activation criteria previously described. Across all cycles (up to 60 possible) for each subject, each muscle was assigned a probability that it was on at a given time. This probability was calculated as the number of cycles during which the muscle was active divided by the total number of cycles. These probabilities were generated for each muscle of each subject and were also combined to generate a group probability of activation for each muscle, as shown in figure 2. For the group data, a muscle was considered active at a particular time if the probability of activation was greater than 0.5.

insert figure 2 here

Results

All subjects were able to perform the exercise bouts, however the intensity with which subjects were able to exercise varied widely. For example, the subject with a T8 incomplete spinal cord injury could easily exercise with a rapid cadence (0.63 cycles/s and a power of 32.3 W) while a subject with cerebellar ataxia, which affected his entire body, exercised at half that intensity (0.37 cycles/s, power: 14.3 W). This appeared to be dependent upon the degree of trunk control a subject had as well as whether a subject's disability affected the upper body (such as for the subject with muscular dystrophy). The total trunk flexion/extension excursion during exercise ranged from $4^{\circ} \pm 1^{\circ}$ to $22^{\circ} \pm 8^{\circ}$. Force versus percent cycle for all subjects are shown in figure 3. Mean power for all subjects was 21.3W, SD 7.1 W.

insert figure 3 here

Elbow kinematics were the most consistent of the joints between subjects and the flexion angle ranged from mean 21° (SD 7° , cycle beginning and end) to mean 116° (SD 23° , mid-cycle).

Data for all subjects are shown in figure 4a. The wrist was generally radially deviated when the elbow was extended and neutral or ulnar deviated during maximal elbow flexion. This occurred because of the straight handlebar that was attached to the device, which prevented free rotation of the wrist during exercise. Because habitual excessive radial/ulnar deviation has been linked to repetitive motion injury [19], the straight handlebar was replaced with two free-moving hand grips mid-way through the testing. However, the total radial/ulnar excursion during the cycle was not different between the two grip types (5.9° for the free-moving hand grips, 7.6° for the straight handlebar, figure 4b) and no other joint kinematics were affected.

insert figure 4 here

The shoulder kinematics of all subjects indicated a general strategy of keeping the elbows elevated (away from the trunk) throughout the cycle. Subjects moved the shoulder from 75° flexion and 42° internal rotation, to 61° abduction and 27° external rotation of the humerus to generate the rowing force. Shoulder kinematic data for all subjects are shown in figure 4c-d. This kinematic pattern was distinctly different from the hypothesized (and instructed) strategy of moving from shoulder flexion to extension without substantial abduction or internal/external rotation.

Electromyography data indicated that peak force production during the drive phase corresponded with co-activation of all measured muscles. The posterior deltoid, latissimus dorsi, biceps and triceps were active for the majority of the drive phase, while the anterior deltoid and trapezius had second activation peaks during the recovery phase of the exercise. These peaks corresponded with shoulder flexion and elbow extension in preparation for another drive phase.

insert figure 5 here

Identified Problems and Solutions

Four subjects commented that they felt uncomfortable pulling hard for fear of falling out of their wheelchair. Limited or absent lower body and trunk control may have prevented these subjects from stabilizing themselves in their wheelchair during the force generating portion of the exercise. Based on these comments, an optional chest restraining strap, which functions to restrain an individual in his or her wheelchair during exercise, has been made available for use with this piece of equipment. The strap wraps around the back of the wheelchair and around the trunk of an individual. It can be worn high on the chest for those individuals with no trunk control, or lower around the hips for more able-bodied wheelchair users. Other commercial devices are available to stabilize wheelchair users within their seat during high-force activities and may be helpful for individuals who habitually engage in this type of exercise.

Despite all subjects being manual wheelchair users who could grip with their hands, we observed that three subjects had difficulty grasping the handlebar sufficiently to generate large forces. This was especially the case for individuals with limited finger strength and dexterity. Two possible solutions exist to address this problem. The first is to add optional wrist straps onto the handle bar, similar to those found on downhill ski poles. This solution has the advantage of being readily available to all users, but the disadvantage of potentially being in the way for users who do not require such assistance. The second solution is to recommend that individuals with this problem use weight lifting wrist straps, which fit around the wrist and include a strap that can be wrapped around a gripping surface. These straps are widely available and function to reduce the gripping force required by the hands by adding an additional frictional surface. They also help distribute the pulling force to the wrist and forearm instead of the hands and fingers. However, they require some amount of dexterity to use effectively.

Three additional changes were made to the accessory unit based on feedback from subjects. First, the height of the pulley was made adjustable to accommodate users of various sizes and with differing chair heights. Second, the resistance of the machine was made adjustable by adding or reducing tension on a spring within the unit. This allowed users to exercise with intensities varying from 10-90 watts. Finally, a bicycle computer was added to the machine so that users had real time feedback of their exercise intensity in the form of “speed.”

Discussion

Our purpose was to develop guidelines for proper exercise execution and recommend design changes to the accessory unit based on user feedback and biomechanical data. Despite instruction and practice, subjects generally kept their shoulders flexed and abducted throughout the exercise cycle. We speculate that this was an attempt to avoid contacting the chair back with the elbows during the force-generating portion of the exercise. In fact, the chair back of most subjects would have allowed shoulder extension without abduction. There is a need to emphasize proper rowing technique and provide more interactive coaching to the subject during the first few exercise sessions on this equipment. Rowing can be excellent for cardiovascular and strength training, but requires careful attention to good technique to avoid injuries [15]. Key kinematic features of a proper drive phase that are relevant to exercise in a wheelchair user include (1) leaning the body slightly forward (if able) with the elbows extended and shoulders flexed around 75°, and (2) drawing the handle towards the lower ribcage while keeping the elbows close to the body and leaning back slightly (if able) [14].

Keeping the elbows close to the body serves two primary purposes: first, it helps keep the wrists in a more neutral position throughout the cycle, minimizing the potential for repetitive motion injury. Second, it strengthens key muscle groups that are associated with reduced

shoulder pain. One such muscle group is the scapular retractors, which include the lower trapezius, rhomboids, and latissimus dorsi. Scapular position influences the position of the humerus within the glenoid and may change the tension of several ligaments within the joint capsule [5]. Spinal cord injured patients frequently experience fatigue of scapular positioning muscles [20], which may contribute to future shoulder problems. Another key muscle group is the shoulder external rotators, which keep the elbows close to the body during rowing. This group includes the posterior deltoid, infraspinatus, and teres minor. Other exercise-based interventions have found that strengthening these two muscle groups can reduce symptoms of shoulder impingement [9].

Despite the excessive shoulder abduction shown by most subjects, the present EMG data show good activation of the latissimus dorsi and the posterior deltoid during the drive phase of the exercise cycle. This suggests that rowing on the accessory unit, even when imperfectly executed, has the potential to strengthen these key groups. However, in the present study data were only collected in the non-fatigued condition and it is possible that muscle activation patterns and kinematics may change as fatigue sets in. Shoulder abduction may also prematurely fatigue the trapezius and anterior deltoids, potentially shortening the duration of the exercise bout. In rowing athletes, over-activation of the upper trapezius and anterior deltoids during the drive phase is associated with the development of shoulder pain, and should therefore also be avoided in wheelchair users [15].

There is currently a limited selection of equipment available to wheelchair users for the purpose of engaging in cardiovascular exercise, and most available equipment is expensive and/or uncommon. For example, arm cycle ergometry requires specialized equipment that is seldom found in community settings. Adaptive rowing requires the use of a modified rowing

ergometer. Modifications must be customized and may include the addition of a seat backrest, seatbelt, and stabilization of the seat along the track to eliminate the need for leg motion. Additionally, users must transfer from their wheelchair into and out of the adaptive ergometer and may require assistance with positioning. Simple overground wheelchair propulsion and propulsion on wheelchair rollers can be excellent cardiovascular and strengthening exercise. However, propulsion as exercise may exacerbate shoulder pain and the potential for repetitive motion injury.

The accessory unit described here provides a potentially more widely available mode of cardiovascular exercise that can be performed without assistance, does not require transferring, and may benefit upper body health and function. Although the accessory unit is not currently commercially available, existing Life Fitness 9500HR stationary cycles can be relatively simply and inexpensively retrofitted. Instructions and a parts list are publicly available and can be accessed at: http://www.rectech.org/demonstration/fact_sheet.php?sheet=2. While the instructions are specific to this model and brand, stationary cycles are often similar in design and many others may be modifiable. Because the accessory unit may be built and used by individuals without access to a personal trainer, a brief guide to proper exercise technique on the accessory unit is provided in figure 6 and is now included in the accessory unit manual.

insert figure 6 here

In summary, kinematic and kinetic data were analyzed on manual wheelchair users as they exercised on an accessory unit that allowed a seated rowing motion. Based on the data, the need to (1) provide a seat belt, (2) provide wrist loops, (3) make the pulley height and resistance adjustable, and (4) emphasize proper exercise technique, were identified. A properly executed rowing exercise may strengthen shoulder external rotators and scapular retractor muscles.

Others have shown that strengthening these muscles may improve shoulder function and reduce pain. Future studies outside the laboratory setting will focus on the effectiveness of a seated row for improving cardiovascular fitness, improving muscle balance around the shoulder, and reducing pain in manual wheelchair users.

Acknowledgements

Funding for this research was provided by NIDRR grant H133E070029. The sponsor was not involved in the study design, collection, analysis and interpretation of data, writing of the manuscript, or in the decision to submit the manuscript for publication. Michael J. Scott, PhD and graduate students were responsible for the design and fabrication of the accessory unit. The 9500HR stationary cycle that was provided by Life Fitness. Ms. Christine Hofmann assisted with data collection.

Declaration of Interest

None to report.

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Figure 1

Figure 2

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Figure 6

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Figure 1 An able-bodied user demonstrates the starting position for exercise on the modified stationary cycle. The shrouds that typically conceal the cycle resistance mechanism have been removed to highlight the accessory unit (white arrows).

Figure 2 Thin gray lines show the probability that the posterior deltoid was active during a particular trial; each thin line represents a single subject. The thick dark line is the mean probability that the posterior deltoid is active for all subjects; the muscle was considered to be active whenever the probability was greater than or equal to 0.5.

Figure 3 Typical pulling force versus percent cycle for all subjects. The time for each subject to complete a single exercise cycle ranged from 1.3 to 2.7 seconds.

Figure 4 (a) elbow flexion, (b) wrist radial/ulnar deviation, (c) shoulder plane of elevation, and (d) shoulder elevation angle. Thick black line represents the group mean, the shaded region is one standard deviation, and the thin lines show individual subjects.

Figure 5 Group muscle activation data. Each curve shows the probability that the muscle was active throughout the cycle. The bars indicate times during which there was a 0.5 or greater chance the muscle was active. Figures at the top show the position of the arms and trunk at key points during the cycle.

Figure 6 During correct execution of the seated row wrists should be close to neutral and the elbows kept no wider than the shoulders. The hands may be oriented horizontally (top row) or

413 vertically (middle row), depending on what is most comfortable. Wrist extension or lateral
414 bending towards the thumb or pinky (radial/ulnar deviation) should be avoided, as should the
415 tendency to elevate the elbows during the drive phase (bottom row).

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