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Short communication

Effect of biceps-to-triceps transfer on rotator cuff stress during upper limb weight-bearing lift in tetraplegia: A modeling and simulation analysis

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ABSTRACT

Rotator cuff stress during upper limb weight-bearing lifts presumably contribute to rotator cuff disease, which is the most common cause of shoulder pain in individuals with tetraplegia. Elbow extension strength appears to be a key determinant of rotator cuff stress during upper limb weight-bearing lifts since individuals with paraplegia who generate greater elbow extensor moments experience lower rotator cuff stress relative to individuals with tetraplegia. Biceps-to-triceps transfer surgery can increase elbow extension strength in individuals with tetraplegia. The purpose of this study was to determine whether active elbow extension via biceps transfer decreases rotator cuff stress during weight-bearing lifts in individuals with tetraplegia. A forward dynamics computational framework was used to estimate muscle stress during the lift; stress was computed as muscle force divided by the peak isometric muscle force. We hypothesized that rotator cuff stresses would be lower in simulated lifting with biceps transfer relative to simulated lifting without biceps transfer. We found that limited elbow extension strength in individuals with tetraplegia, regardless of whether elbow strength is enabled via biceps transfer or is residual after spinal cord injury, results in muscle stresses exceeding 85% of the peak isometric muscle stress in the supraspinatus, infraspinatus, and teres minor. The rotator cuff stresses we estimated suggest that performance of weight-bearing activities should be minimized or assisted in order to reduce the risk for shoulder pain. Our results also indicate that biceps transfer is unlikely to decrease rotator cuff stress during weight-bearing lifts in individuals with tetraplegia.

1. Introduction

Individuals with tetraplegia after spinal cord injury (SCI) rely on their upper limbs for mobility and other activities that are important for independent living. Preservation of upper limb function by minimizing the risk for pain is imperative for long-term independence because pain is associated with additional losses in function (Pentland et al., 1994; Ballinger et al., 2000). Unfortunately, pain is prevalent in individuals with tetraplegia, particularly in the shoulder joint (Sie et al., 1992; Subbarao et al., 1995). In two different studies, 78% and 89% of individuals with tetraplegia reported shoulder pain (Curtis et al., 1999; Medina et al., 2011). Rotator cuff disease, which is degeneration of the rotator cuff tendons, is the most common cause of shoulder pain in tetraplegia (Sie et al., 1992; Campbell et al., 1996). High and repetitive rotator cuff stresses during upper limb weight-bearing tasks presumably contribute to rotator cuff disease. Upper limb weight-bearing tasks are routinely performed by individuals with SCI to transfer into and out of the wheelchair, and to prevent pressure ulcers.

Elbow extension strength appears to be a key factor in determining the ability of an individual to achieve a weight-bearing lift independently (Staas Jr., 1998; van Drongelen et al., 2006, Lamberg et al., 2011) and rotator cuff stress during a lift (van Drongelen et al., 2005; van Drongelen et al., 2006). Individuals with C5 tetraplegia lacking active elbow extension rarely can achieve a lift

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independently (Staas Jr., 1998). Individuals with C6 tetraplegia with limited active elbow extension may achieve a lift by passively extending the elbow and bearing weight through the upper limb (Gefen et al., 1997; Harvey et al., 2000; Newsam et al., 2003; van Drongelen et al., 2005). In contrast to individuals with tetraplegia, individuals with paraplegia achieve a weight-bearing lift using the elbow extensors and larger thoracohumeral muscles with little rotator cuff activity (Reyes et al., 1995; Newsam et al., 2003) and reduced rotator cuff stress (van Drongelen et al., 2005).

Voluntary elbow extension strength can be increased in individuals with C5 or C6 tetraplegia via biceps-to-triceps transfer: a surgical procedure that reassigns the insertion tendon of a non-paralyzed biceps to the insertion site of the paralyzed triceps. The purpose of this study was to determine the potential of active elbow extension via biceps transfer to decrease rotator cuff stress during weight-bearing lifts in individuals with tetraplegia. We generated forward dynamics simulations to estimate stress because muscle stress cannot be directly measured *in vivo* during movement. We hypothesized that rotator cuff stresses would be lower in simulated lifting with biceps transfer relative to simulated lifting without biceps transfer.

2. Methods

2.1. Experimental data

Wheelchair users with cervical SCI were recruited for participation. Six individuals provided informed consent and participated (Supplementary Table A). The experimental protocol was approved by the Institutional Review Board of Northwestern University. Kinetic data were recorded during maximum voluntary isometric contractions (MVICs) to measure upper limb strength. Joint moments were recorded from a six degree-of-freedom load cell (30E15; JR3, Woodland, CA), which was interfaced with the Biodex (850-000; Biodex Medical Systems, Inc., Shirley, NY) dynamometer shaft with a custom made assembly. The load cell allowed for greater resolution of moments (0.001 N-m) relative to the Biodex dynamometer (1.36 N-m). Kinetic data were acquired at 1000 Hz using an 18-bit analog to digital converter (NI - PCI 6289; National Instruments Austin, TX). After the MVIC protocol, subjects were transferred to an electro-hydraulic chair positioned between two adjustable hand rails (Supplementary Figure A). The load cell was interfaced with a custom built handrim to record forces during weight-bearing trials. Kinematic data were recorded via infrared markers sampled at 74 Hz. Subjects completed six weight-bearing lift trials; they were instructed to lift their body weight using their upper extremities to the best of their ability.

2.2. Musculoskeletal models

Two subjects were selected for modeling and simulation analyses based on their ability to perform a weight-bearing lift independently and their injury classification of C5 or C6 tetraplegia (Supplementary Table B). A musculoskeletal model of the nonimpaired, right upper limb (Saul et al. 2015) was adapted to model: 1) a subject with C6 tetraplegia and residual triceps function (female, 36 years old, 64.9 kg body mass, 3/5 manual muscle grade for triceps, referred to hereafter as the Residual Triceps subject), and 2) a subject with C5 tetraplegia and biceps-to-triceps transfer (male, 29 years old, 56.6 kg body mass, referred to hereafter as the Biceps Transfer subject) using SIMM (Musculographics, Inc., Santa Rosa, CA). Polynomial equations created by Rankin and Neptune, 2012 defined musculotendon lengths and moment arms. To model the biceps transfer, we defined the muscle line-of-action for the biceps based on surgical description of the medial route provided by surgeon M.S.B. (Supplementary Table C). Musculotendon lengths of the transferred biceps were fit with a polynomial equation (Supplementary Methods and Table C) using a least-squares fitting method (Menegaldo et al., 2004; Rankin and Neptune, 2012).

Peak isometric muscle force is the absolute maximum isometric force a muscle can generate. Peak isometric muscle forces defined in the nonimpaired upper limb model (Saul et al., 2015) were scaled to represent the strength of each subject with tetraplegia (Supplementary Tables D and E) using a technique previously described (Mogk et al., 2011). Strength scaling ratios were computed as the maximum moment generated by the subject divided by the maximum moment generated by the nonimpaired model in the same isometric position. Segment inertial properties were scaled by the ratio of subject body mass to the mass of a 50th percentile male (75 kg, basis of the nonimpaired model's inertial parameters). Specifically, segment masses and mass moments of inertia in the nonimpaired model were multiplied by 0.87 and 0.75 to model the Residual Triceps and Biceps Transfer subjects, respectively. Thorax inertial properties derived from Dumas et al. (2015) were scaled in a similar manner.

2.3. Forward dynamics simulations of weight-bearing lifts

One simulation was generated for each of the two subjects using an optimization approach such that the resulting simulation reproduced the kinematics of the weight-bearing lift recorded from that subject in one representative experimental trial. A simulated annealing algorithm (Goffe et al., 1994) was used to determine muscle excitations that minimized the difference in the simulated and experimental joint angles, and total muscle stress. Simulated kinematics replicated the motion of the representative experimental trial when the simulated motion was within two standard deviations of the experimental data for each joint. Standard deviations of the experimental kinematic data for each joint were computed across all six trials collected per subject (Figs. 1 and 2). Musculotendon actuators were combined into muscle groups based on their anatomical classification (Table 1) and each received the same excitation signal ranging from 0 to 1. To model the initial support of the subject against gravity via the chair, a force opposing gravity was applied to the thorax center-of-mass. This force was equal to the total model mass multiplied by gravitational acceleration at the start of the simulation, then decreased to zero at a rate scaled by the handrim force opposing gravity. External forces recorded at the handrim, corresponding to the selected representative trial, were applied to the palm segment (Figs. 1 and 2).

After the convergence criteria were satisfied, muscle forces were computed at each time step. Muscle forces during the lift were divided by the peak isometric muscle force to estimate muscle stress. This measure of muscle stress is equivalent to normalizing muscle stress at each time step to the peak isometric muscle stress (i.e., stress at peak isometric force). For further details regarding the study methodology, please see the Supplementary Methods.

3. Results

3.1. Rotator cuff muscle stresses

Muscle stress during weight-bearing lifting reached at least 85% of peak isometric muscle stress in the supraspinatus, infraspinatus and teres minor for both subjects that we simulated (Table 2). The largest muscle stress in the Biceps Transfer subject occurred in supraspinatus (115%, passive muscle force was generated such that the muscle stress exceeded the peak isometric muscle stress), which was the largest stress experienced by any muscle during

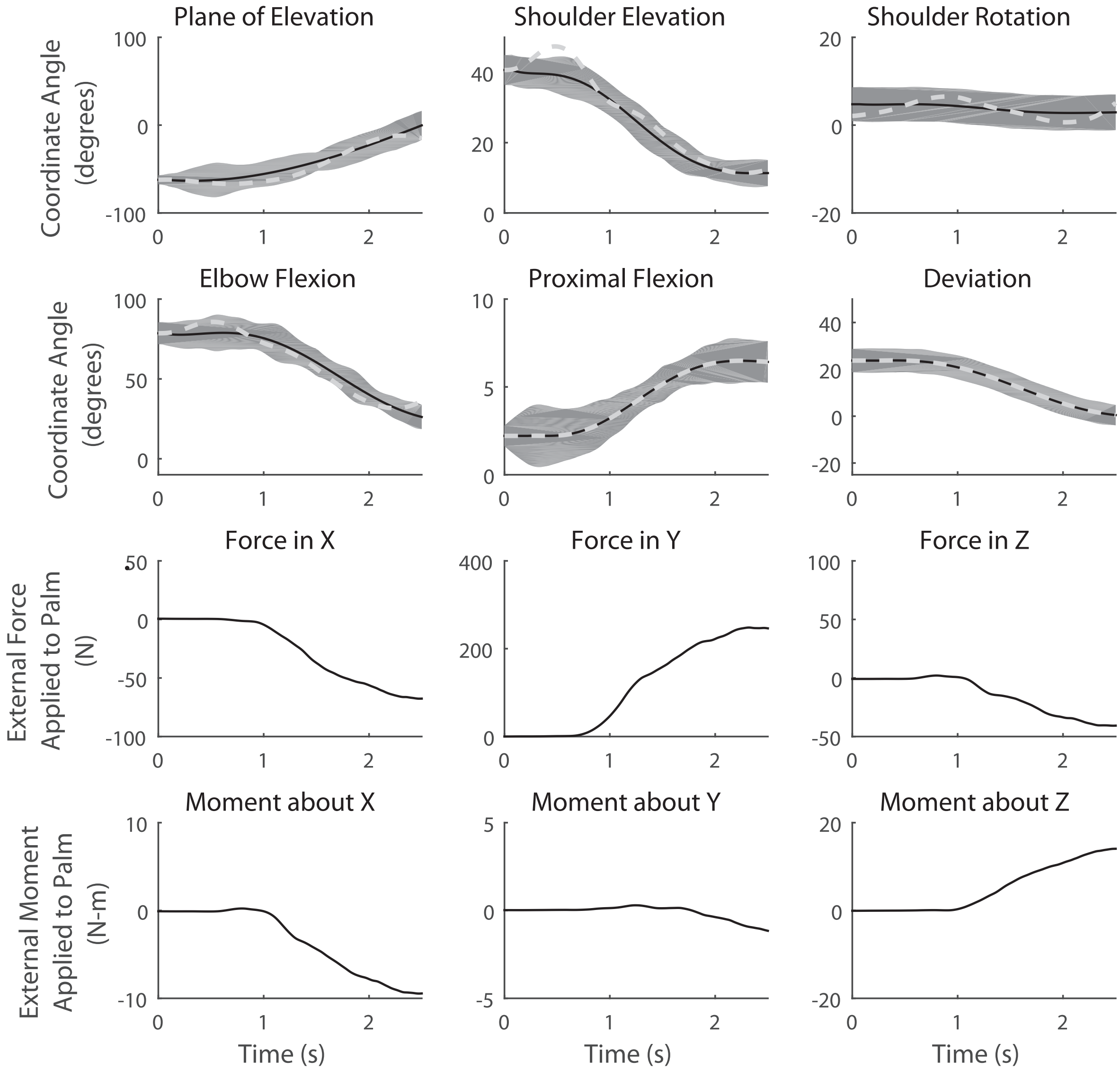

Fig. 1. Comparison of the experimental (solid lines) and simulated (dashed lines) kinematics during the lift phase for the Residual Triceps subject. Grey shading indicates ± two standard deviations; standard deviations were computed across six weight-bearing lift trials. Proximal flexion and deviation coordinate angles were prescribed to match the experimental data. External forces recorded at the handrim were applied to the palm segment. See Supplementary Figure A for the definition of the X, Y, and Z directions.

the simulated lifts. For the subscapularis, the largest muscle stress during the lift was 45% and 70% of the peak isometric stress for the Residual Triceps and Biceps Transfer subjects, respectively.

3.2. Elbow muscle stresses

Simulated elbow muscle stresses differed between the Residual Triceps and Biceps Transfer subjects during the lift. The largest stresses in the transferred biceps short and long heads (acting to extend the elbow) were 84% and 78% of the peak isometric muscle stress, respectively (Table 2). The largest stresses during the lift in the biceps short and long heads of the Residual Triceps subject were 45% and 51% of the peak isometric muscle stress, respectively.

4. Discussion

The purpose of this study was to determine the potential of active elbow extension via biceps transfer to decrease rotator cuff stress during weight-bearing lifts in individuals with tetraplegia. We hypothesized that rotator cuff stresses would be lower in the simulation of the individual with biceps transfer relative to the individual without. Contrary to our hypothesis, we found that the largest stresses during the lift were similar between subjects, exceeding 85% of the peak isometric muscle stress in the supraspinatus, infraspinatus, and teres minor muscles in both subjects with tetraplegia. Therefore, individuals with tetraplegia, both with and without biceps transfer, are at increased risk for shoulder pain and injuries associated with upper limb weight-bearing and rotator cuff degeneration.

The rotator cuff stresses we estimated in both the Biceps Transfer and Residual Triceps subjects with tetraplegia suggest that performance of weight-bearing activities should be minimized or assisted in order to reduce the risk for shoulder pain. To achieve pressure relief independently, our results support the use of forward leans rather than weight-relief lifts if individuals have adequate trunk strength. Forward leaning for two minutes effectively relieves pressure similar to holding a weight-relief lift

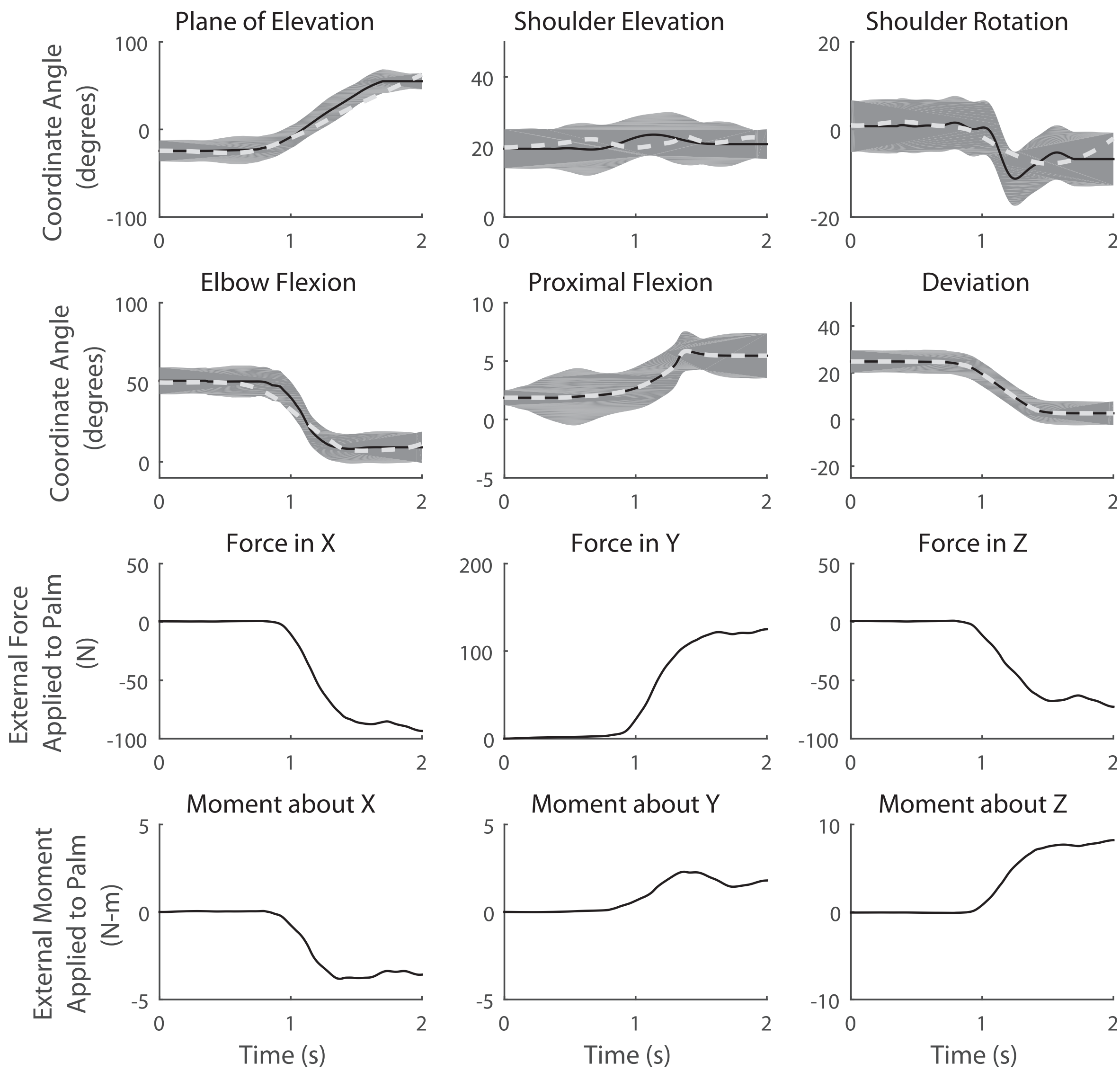

Fig. 2. Comparison of the experimental (solid lines) and simulated (dashed lines) kinematics during the lift phase for the Biceps Transfer subject. Grey shading indicates ± two standard deviations; standard deviations were computed across six weight-bearing lift trials. Proximal flexion and deviation coordinate angles were prescribed to match the experimental data. External forces recorded at the handrim were applied to the palm segment. See Supplementary Figure A for the definition of the X, Y, and Z directions.

for two minutes (Coggrave and Rose, 2003). To minimize rotator cuff stress while transferring into and out of the wheelchair, future work should consider the design of passive or active exoskeletons that can redistribute loading and assist individuals with independent transferring to reduce the demand on the shoulder.

The rotator cuff muscle stresses we estimated were higher than previous simulation analyses of weight-bearing lifts by individuals with tetraplegia without tendon transfer (van Drongelen et al., 2005), suggesting that stress is underestimated if models are not scaled to represent patient strength. We scaled the peak isometric muscle forces in our models based on the maximum isometric joint moments we recorded from the subjects that we modeled. van Drongelen et al. (2005) estimated rotator cuff stress to range between approximately 7 and 40% of peak isometric muscle stress in individuals with tetraplegia, in contrast to the range of 45–115% of peak isometric stress in our study. Peak isometric muscle forces in their model were based on nonimpaired strength. Thus, while the muscle forces during weight-bearing lifts in tetraplegia that we estimated were comparable to muscle forces estimated previously (van Drongelen et al., 2005), our estimates of muscle stress were higher.

Increased elbow extension strength via biceps transfer may have provided lifting ability in the individual we analyzed. Evidence to support the contribution of biceps transfer to lifting ability was the four times greater force generated by the biceps in the Biceps Transfer subject relative to the biceps in the Residual Triceps subject (Table 2). However, we did not assess lifting ability prior to tendon transfer surgery. Another limitation of our study is that we modeled each musculotendon actuator as one element, while failure stresses differ across tendinous regions in these muscles (Itoi et al., 1995; Halder et al., 2000a, Halder et al., 2000b). Another potential limitation is that we used a unilateral upper limb model that statistically predicts the orientation of the clavicle and the scapula (origin of the rotator cuff muscles) from the humerus orientation.

5. Conclusions

Limited elbow extension strength in individuals with tetraplegia, regardless of whether elbow strength is enabled via biceps-to-triceps transfer or is residual after SCI, can result in muscle

Table 1
Upper extremity muscle and group definitions for models of the Residual Triceps subject and the Biceps Transfer subject.

Group	Muscle	Abbreviation	Residual Triceps: Peak isometric force (N)	Biceps Transfer: Peak isometric force (N)
SUPSP	Supraspinatus	Supra	159.7	89.9
SUBSC	Subscapularis	Subsc	457.2	261.4
INF	Infraspinatus	Infra	322.7	301.2
TMIN	Teres minor	Tmin	80.9	75.5
AD	Anterior deltoid	Adelt	390.0	219.4
MD	Middle deltoid	Mdelt	353.1	198.6
PD	Posterior deltoid	Pdelt	66.5	36.3
PEC1	Pectoralis major – clavicular head	PECclav	142.2	80.0
PEC2	Pectoralis major – sternocostal head (sternum)	PECst1	171.2	118.5
	Pectoralis major – sternocostal head (ribs)	PECst2	129.5	89.7
CORB	Coracobrachialis	Corb	54.1	37.5
LAT	Latissimus dorsi - thoracic	Lat1	95.9	52.3
	Latissimus dorsi - lumbar	Lat2	104.8	57.2
	Latissimus dorsi - iliac	Lat3	62.4	34.0
	Teres major	Tmaj	47.5	25.9
TRI	Triceps brachii lateral head	TRIlat	193.7	71.8
	Triceps brachii medial head	TRImed	193.7	71.8
	Triceps brachii long head	TRIlong	208.4	77.2
	Anconeus	Anc	76.5	28.3
BIC	Biceps brachii short head	BICshort	60.2	148.9
	Biceps brachii long head	BIClong	99.8	246.8
BRD	Brachialis	Bra	223.7	423.9
	Brachioradialis	Brd	52.4	99.4

Table 2
The largest muscle forces and stresses generated during the simulated weight-bearing lift by the Residual Triceps and Biceps Transfers subjects.

	Residual Triceps		Biceps Transfer	
Muscle	Force (N)	Stress (%)*	Force (N)	Stress (%)*
Supra	137	86	103	115
Subsc	207	45	183	70
Infra	293	91	290	96
Tmin	70	86	64	85
Adelt	320	82	157	72
Mdelt	39	11	132	66
Pdelt	39	59	39	108
PECclav	114	80	73	92
PECst1	90	53	55	46
PECst2	30	24	23	26
Corb	37	69	26	68
Lat1	72	75	40	77
Lat2	75	72	41	72
Lat3	54	86	28	83
Tmaj	44	92	25	96
TRIlat	134	69	59	82
TRImed	131	68	56	78
TRIlong	182	87	31	40
Anc	53	69	3	11
BICshort	27	45	126	84
BIClong	51	51	192	78
Bra	191	85	382	90
Brd	42	80	89	90

* Muscle stresses during the weight-bearing lift were computed as muscle force during the lift divided by the peak isometric muscle force (see Table 1).

stresses exceeding 85% of the peak isometric stress in the supraspinatus, infraspinatus, and teres minor. The rotator cuff stresses we estimated through simulation analyses suggest that even if individuals with tetraplegia are able to achieve a lift, performance of weight-bearing activities should be minimized or assisted in order to reduce the risk for shoulder pain. Forward leans to prevent pressure ulcers and the design of exoskeletons to assist with transferring into and out of the wheelchair are encouraged. Our results also indicate that biceps transfer is unlikely to decrease rotator cuff stress during weight-bearing lifts in individuals with C5 or C6 tetraplegia.

Declaration of Competing Interest

The authors have no conflicts of interest to disclose.

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Appendix A. Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.04.043.

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