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Model-based development of neuroprostheses for restoring proximal arm function

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Abstract—Neuroprostheses with the use of functional neuromuscular stimulation (FNS) have the potential to restore elbow and shoulder function lost to paralysis because of spinal cord injury (SCI). The human shoulder is highly flexible and thus provides a large range of motion to the arm and hand, although at the expense of precarious stability of the articulations. The complexity of the shoulder has prevented widespread use of FNS at this joint. However, musculoskeletal modeling of the elbow and shoulder has the potential to significantly speed the development of neuroprostheses by allowing many mechanical issues to be resolved in simulation prior to implementation in human subjects. This paper describes our rationale for the use of musculoskeletal modeling, the model we are using, and several practical applications of the model to study the potential use of shoulder and elbow muscle FNS to restore function following cervical SCI.

Key words: *arm movement, FES, FNS, modeling, musculoskeletal, SCI, shoulder, spinal cord injury, tetraplegia.*

INTRODUCTION

The ultimate goal of the work described here is to restore arm function to individuals with cervical-level spinal cord injury (SCI) with the use of functional neuromuscular stimulation (FNS) and reconstructive surgeries. The importance of the shoulder in producing such movements cannot be underestimated. The shoulder is flexible enough to provide the arm with an enormous range of motion, yet it can simultaneously provide a stable platform for the arm during even very strenuous forces exerted against the environment. These functions are mediated by a large number of muscles, many of which cross multiple articulations and many of which have complex internal architectures (1,2). When an individual sustains a cervical-level SCI, the muscles of the shoulder are affected to a degree dependent upon the particular level of the injury (3). This paper will focus on two general groups: individuals with mid-level (C5–C6) cervical SCI and

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individuals with high-level (C1–C4) cervical SCI. Because of the mechanical complexity of the human shoulder, efforts to restore function with the use of FNS, reconstructive surgeries, and other techniques have been few and not particularly effective. We believe that the tool of musculoskeletal modeling provides a way of managing this complexity, thus facilitating the development of interventions to restore function to the arm in these individuals.

Shoulder Anatomy and Mechanics

The human shoulder is an amazing set of articulations (see **Figure 1(a)**) that provides the largest range of motion of any "joint" in the body (1,2). The glenohumeral joint is the ball and socket joint that connects the upper arm (humerus) to the scapula (glenoid fossa). The glenoid fossa is the articulating surface ("socket") within the scapula. It is quite shallow and small, with a surface area approximately one-third that of the humeral head (see **Figure 1(b)**). The scapula is a flat, roughly triangular bone that glides on the posterior thorax. It rotates and translates significantly during normal movements but must also be tightly clamped against the thorax while the arm exerts strong forces against the environment. The clavicle is a strut that connects the scapula to the thorax at the sternum—the sternoclavicular joint is actually the only skeletal connection between the humerus and the rest of the body. During normal movements, the relative motions of these bones are finely coordinated to move together in a set of "rhythms." For example, elevation of the arm from the side to overhead is achieved through a combination of glenohumeral rotation (about two-thirds of the total motion) and scapular lateral rotation (about one-third) in a highly repeatable and synchronized fashion.

The combination of a small, shallow glenohumeral articulation, a floating scapula, and multiple degrees of freedom provides the shoulder with its incredible range of motion. However, a reliance on soft tissues (joint capsule, ligaments, and particularly muscles) to maintain the integrity of the joint results in a precarious attachment of the arm to the body. The shoulder is susceptible to dislocation and pain even in the able-bodied population, and this situation is significantly exacerbated in individuals with weakness and paralysis caused by cervical SCI.

Shoulder motions and internal stability are provided by a large set of rather complex muscles. A number of large, powerful muscles such as the deltoid, pectoralis major, and latissimus dorsi generate the forces needed to

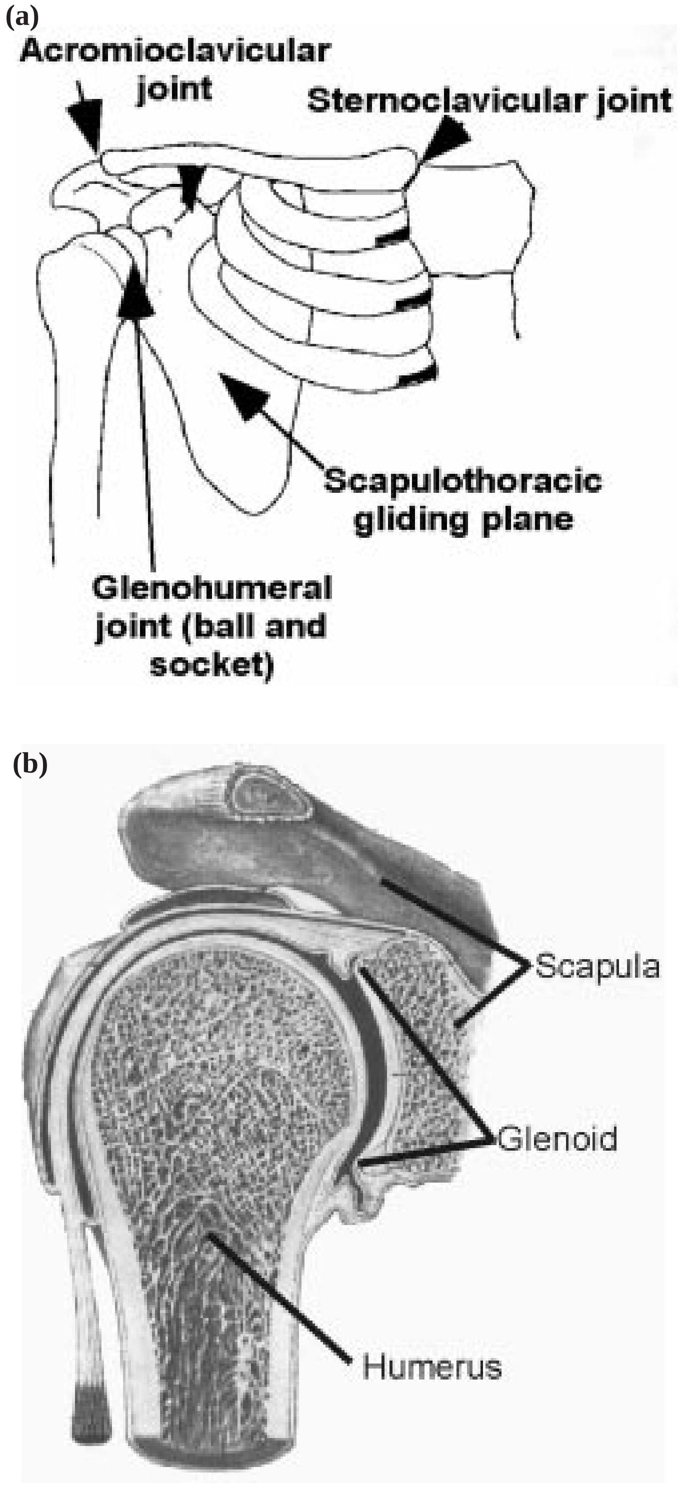


Figure 1
(a) Basic structure of the human shoulder indicating bones and articulations of shoulder and (b) cross section through the proximal humerus and lateral scapula to illustrate the small and shallow socket provided by glenoid fossa of scapula.

move the mass of the arm and to exert forces against the environment. As illustrated in **Figure 2**, the rotator cuff muscles (infraspinatus, supraspinatus, subscapularis, and teres minor) stabilize the head of the humerus within the shallow glenoid fossa. The serratus anterior participates in the rotation and fixation of the scapula. All of these muscles are normally finely coordinated to produce the observed "rhythms" and various functions of the shoulder.

Effects of Cervical SCI on Shoulder Function

As indicated in **Figure 3**, the muscles of the shoulder and elbow primarily receive their spinal innervation from cervical levels, so SCI in this region affects shoulder function to a degree dependent on the level and extent of the injury. The shading in **Figure 3** illustrates the state of these muscles in an individual with a generic C5-level SCI. The term "C5 SCI" refers to the lowest spinal level with retained function, so the injury actually occurred at the C6 spinal cord level. Motoneurons arising from levels below a complete SCI will be paralyzed (gray shading in **Figure 3**), while those from levels above the injury will remain under voluntary control (no shading in **Figure 3**). Motoneurons in the region of the injury (black shading in **Figure 3**) may die, causing denervation and preventing the possible use of FNS. Because most shoulder muscles receive innervation from two or more levels, they may exhibit a mixture of voluntary control, denervation, and paralysis. Individuals with C5 SCI will retain partial function of the elbow flexors and glenohumeral muscles (e.g., deltoid and rotator cuff), so these muscles may be weak. The elbow extensors and several prominent shoulder muscles (pectoralis major, latissimus dorsi) will be mostly or completely paralyzed, resulting in the inability to raise the arm above horizontal or toward the midline, as well as lack of shoulder adduction. For higher-level injuries (C4 and above), the shaded areas in **Figure 3** would shift to the left, reflecting the paralysis and/or denervation of basically all shoulder and elbow muscles other than the trapezius. Thus, all shoulder and arm function except shoulder shrug is typically lost.

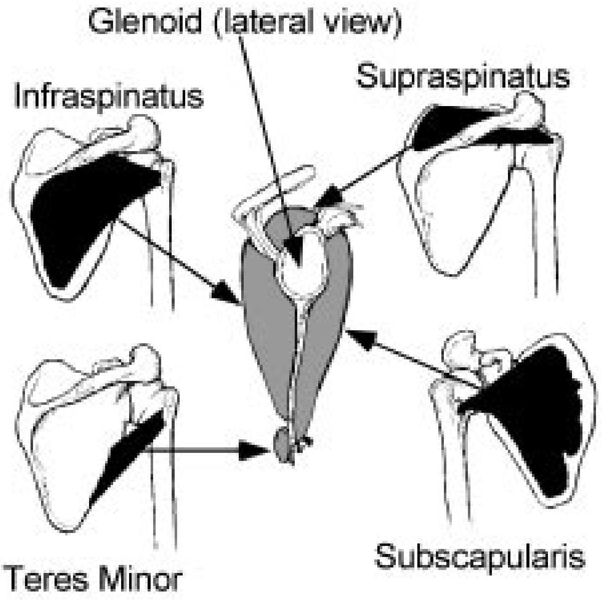


Figure 2.
Anatomy and function of rotator cuff muscles. Anterior (subscapularis) and posterior (infraspinatus, supraspinatus, teres minor) views of each of rotator cuff muscles are illustrated, along with a lateral view of all four muscles and their anatomical relation to glenoid fossa.

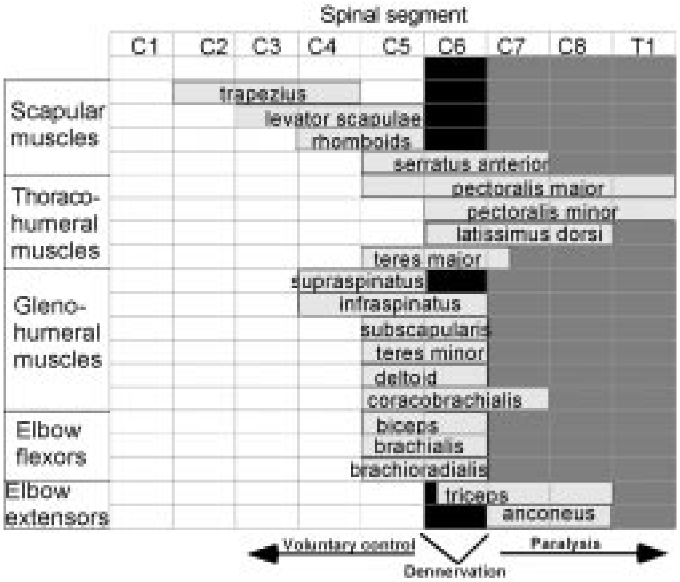


Figure 3.
Spinal innervation of muscles of human shoulder and elbow. Muscles are divided into five basic groups (scapular, thoracohumeral, glenohumeral, elbow extensors, and elbow flexors) to indicate general function. Horizontal bar for each muscle indicates spinal segments from which muscle receives innervation. Shaded areas indicate hypothetical effects of an individual with a pure C5 spinal cord injury. Black shading indicates denervation, gray shading paralysis, and no shading voluntary control.

Musculoskeletal Modeling of the Shoulder and Elbow

Musculoskeletal modeling is the mathematical description of a joint or limb that contains individual components such as the skeletal geometry, the joints (relative motions between adjacent bones), ligaments, and muscle-tendon units. Computer-based simulations can be performed with such models to evaluate the mechanical response of the system to its inputs (e.g., muscle-activation levels) or to determine the inputs needed to achieve a particular mechanical state. Constructing large-scale musculoskeletal models often requires assumptions and simplifications to achieve a stable simulation that can be performed within a reasonable duration. This paper will not focus on the current capabilities and limitations of musculoskeletal modeling. Rather, the focus here is on the motivation for developing and using such models.

Particularly in a complex system such as the human shoulder, musculoskeletal modeling offers several significant advantages over alternative approaches. Neuroprostheses for improving shoulder function will undoubtedly require invasive surgeries to place components within the body. During at least the initial phases of development, simulations performed with a musculoskeletal model can take the place of human experimentation, and the model can be subjected to a barrage of otherwise tedious, invasive, and potentially unsuccessful intermediate implementations. The basic feasibility of an approach can be evaluated; e.g., is it even mechanically possible to restore a particular function through FNS of a reasonable number of paralyzed muscles? The effects of various muscles sets can be evaluated in simulation, as can the surgical transfer of muscles to replace those where denervation is too severe to allow effective stimulation. Finally, the model can be placed within a proposed control system so that the feasibility of the controller can be evaluated and the effects of modifying various controller parameters can be investigated off-line prior to human implementation.

We have adopted the shoulder model developed by Frans van der Helm and colleagues at the Technical University at Delft (4,5). This model, the structure of which is illustrated in schematic form in **Figure 4**, contains anatomically accurate descriptions of the various bones of the arm and shoulder, the articulations between these bones, several important ligaments, and 30 or more muscles crossing the various articulations. In many cases, the muscles are subdivided into five to nine subelements to reflect the wide origins and/or insertions of the muscles. Glenohumeral and scapular stability are addressed through constraints that require the net glenohumeral reaction force vector to be directed into the glenoid fossa and the scapula to direct positive force against the thorax. We continue to develop methods to adjust the parameters of this model to reflect cervical SCI of various levels. Several applications of this model will be described below, but in general we are interested in using model-based simulations in the following ways:

- To explore the feasibility of restoring specific functions to specific individuals or populations. Is it feasible with a reasonably achievable neuroprosthesis? What function can be added by reconstructive surgeries?
- Investigate internal shoulder stability following SCI and, in particular, the effects of FNS of both large “prime movers” and stabilizing muscles on this stability.
- To develop control algorithms for shoulder FNS systems.

RESULTS

Applications in Mid-Cervical (C5–C6) SCI

As described above, individuals with C5 SCIs have paralysis of a number of muscles, including the pectoralis major and latissimus dorsi. This results in the loss of shoulder adduction and in very weak shoulder horizontal flexion. Loss of adduction prevents stabilization of the arm at the side (i.e., at laptop and tabletop levels) and the inability to perform more forceful maneuvers, such as weight shifts and transfers from one seating surface to another. Horizontal flexion loss prevents movements of the hand toward the mid-line and any manipulation activity that would normally be performed in this region. In one study, we performed an extensive series of simulations to determine whether these two functions could be enhanced by stimulation of a small set of muscles, and determined the muscles likely to be the most effective targets for stimulation. A second study examined the impact on glenohumeral stability of stimulating the large muscles needed to enhance external arm function, as well as the potential of rotator cuff function to compensate for any destabilizing conditions.

Muscle Selection for Adduction and Horizontal Flexion

An extensive series of inverse simulations was performed to determine the relative strength gains in shoulder adduction and horizontal flexion that might be achieved by adding stimulated muscles to the voluntary musculature of an individual with C5 SCI. This assessment was performed by modifying the shoulder model (the elbow was not considered in this study) to reflect C5 SCI and then performing inverse simulations with increasing

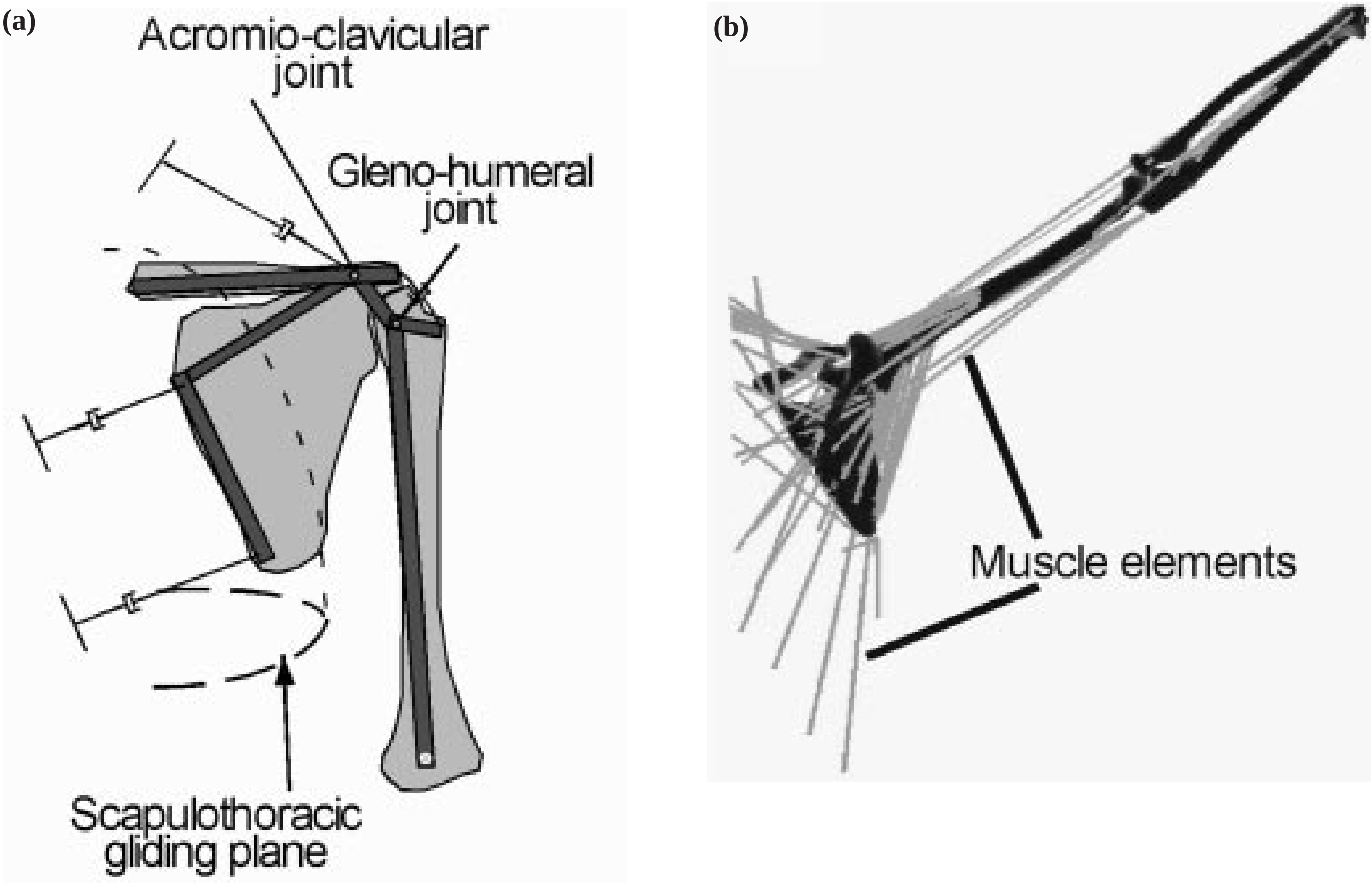


Figure 4.
Schematic representations of Delft shoulder model (4,5): (a) indicates beam structures used to approximate bones of shoulder and articulations between bones and (b) is a graphical representation of muscle elements used in this model.

external loads in horizontal flexion and adduction until the model could no longer find a feasible solution. Paralyzed muscles (pectoralis major clavicular head, pectoralis major sternocostal head, pectoralis minor, latissimus dorsi, serratus anterior, and coracobrachialis) were added back in all possible combinations (one at a time, two at a time, etc., up to all six at once; a total of 63 combinations) to determine the increase in these external moments that could result from FNS of these muscles. We found that stimulation of four muscles (pectoralis major thoracic, latissimus dorsi, coracobrachialis, and serratus anterior), in addition to the voluntary musculature, could produce 97 percent of the forces produced by all six muscles. Indeed, more than 90 percent of the maximum effect could be achieved whenever the latissimus dorsi and pectoralis major thoracic were combined with either the coracobrachialis or serratus anterior. The functional significance of these additional shoulder forces is illustrated in **Figure 5**, which plots adduction force (top panel) and horizontal flexion force (bottom row of panels) as functions of arm position. Adduction is shown only for the abduction plane, i.e., with the arm to the side. It can be seen in this figure that the voluntary adduction strength (“C5 vol”) is barely more than the effect of gravity on the mass of the arm. However, including stimulation of pectoralis major thoracic, latissimus dorsi, coracobrachialis, and serratus anterior increases the adduction moment (“C5 vol + stim”) so that it is essentially equivalent to the much stronger moments that can be produced by a model reflecting an individual with a C6 level SCI. Likewise, the horizontal flexion moment that was added by “stimulation” of these same four muscles in most arm positions increased strength to a level similar to a C6 level SCI subject. Thus, it appears that stimulation of just four muscles has the potential to raise the functional level of an individual with a C5 SCI by at least one segment.

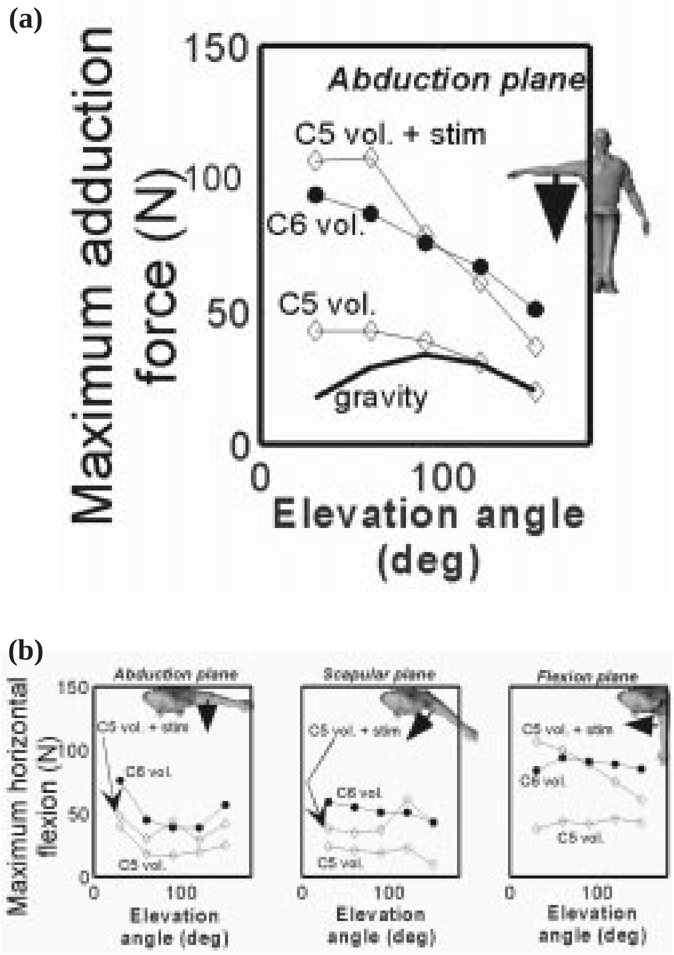


Figure 5.
Simulated effects of shoulder muscle stimulation in individuals with C5 level SCI. All panels of this figure plot forces acting at distal end of humerus as result of shoulder abduction (a) or horizontal flexion (b). (a) Illustration of maximum abduction forces that could be generated by model with C5 voluntary muscles (labeled "C5 vol"), C6 voluntary muscles (labeled "C6 vol"), and C5 voluntary muscles plus stimulation of thoracic pectoralis major, latissimus dorsi, coracobrachialis, and serratus anterior muscles (labeled "C5 vol + stim"). For reference, forces caused by gravity acting on mass of arm are indicated by thick curve. (b) Illustration of corresponding horizontal flexion forces for same conditions as in (b). Three panels (from left to right) illustrate these forces with arm held in abduction, scapular, and flexion planes.

Effects of Pectoralis Major, Latissimus Dorsi, and Rotator Cuff Muscles on Glenohumeral Stability

The previous study clearly indicated that stimulation of pectoralis major thoracic and latissimus dorsi can lead to significant increases in shoulder strength. However, it is critical to maintain the stability of the glenohumeral joint during such stimulation to prevent further shoulder impairment, pain, and permanent deformity that could result from repeated stimulation-induced subluxation. A second simulation study was therefore performed to estimate changes in the origin of the net glenohumeral reaction force vector when "stimulated" muscles were added to the equilibrium produced by the "voluntary" musculature. This study evaluated only arm positions within the abduction plane (i.e., the arm elevating to the side). At a series of arm elevation angles, a set of "voluntary" muscle activations was computed that would produce a stable force equilibrium; i.e., the arm could be held against gravity and the net glenohumeral force vector had an origin within the glenoid, indicating stability. An additional force caused by one "stimulated" muscle was then added in gradually increasing magnitudes, from 10 to 100 percent of maximum in 10 percent increments. For each added force, the net (voluntary forces plus "stimulated" force) reaction force vector was recomputed to determine the effects on glenohumeral stability.

The results are illustrated in **Figure 6**. Each ellipse is an idealized outline of the glenoid. The different ellipses represent different arm elevation angles, with elevation angle increasing from the bottom panel in the figure to the top panel. The point indicated by the crossed circle symbol within each ellipse is the origin of the glenohumeral force vector with only "voluntary" muscles. The left column of ellipses indicates the effects of stimulating pectoralis major (open circles) and latissimus dorsi (filled circles). The pectoralis major pulls the net reaction force forward and downward and leads to an unstable glenohumeral joint (i.e., the force origin is outside of the ellipse) in all arm positions for even small "stimulated" forces. On the other hand, the latissimus dorsi has a stabilizing effect at all but the highest arm elevation angles because it pulls the force vector origin down from its initially high location. The rotator cuff muscles (right column) have almost universally stabilizing actions, pulling the force vector origin toward the center of the glenoid. In most arm positions, the rotator cuff appears well suited to counteract any destabilizing actions of the pectoralis major. The paralysis/denervation status of the rotator cuff muscles in C5 SCI is not precisely known. Thus, it may be that the stabilizing effects of these muscles can be produced under voluntary control or may require FNS.

Applications in High Tetraplegia (C1–C4 SCI)

As noted above, individuals with high-level tetraplegia (C1–C4 SCI) lose all arm function except shoulder

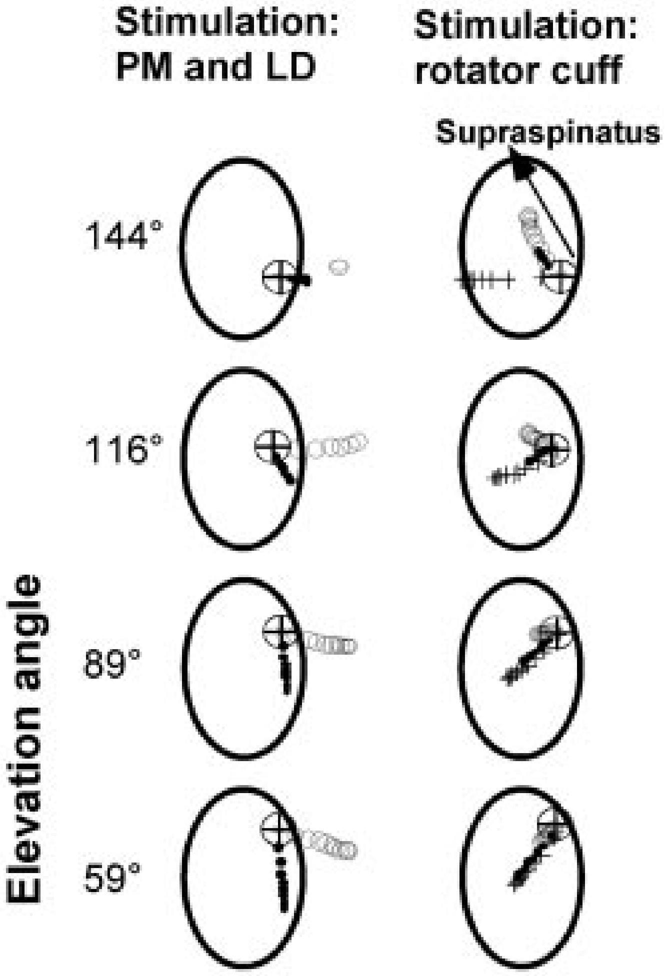
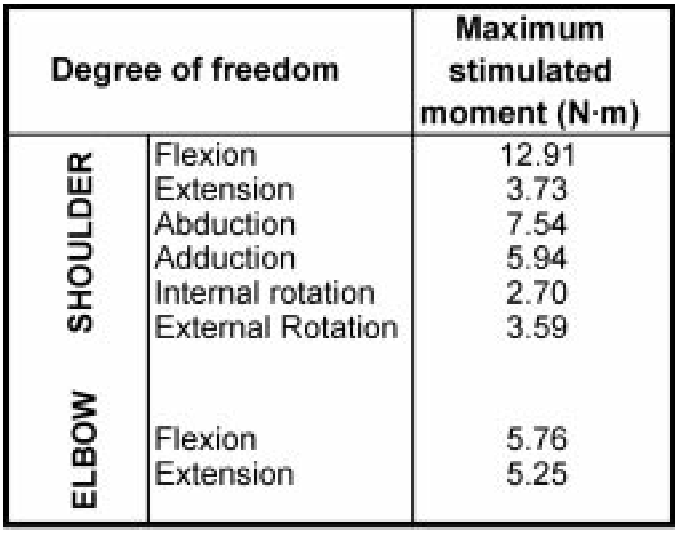


Figure 6.
Simulated effects of shoulder muscle stimulation on glenohumeral stability. Each of ellipses shown in this figure indicates a lateral view of glenoid. Model has been modified to reflect a C5 SCI. Crossed circle in each ellipse shows origin of net glenohumeral force vector computed when arm is held in one of six positions in abduction plane by voluntary muscle activation. Left column indicates effect on force vector origin when additional forces (10 to 100 percent of maximum force in 10 percent increments, with forces increasing in direction indicated by arrow in lowest panel) are added by pectoralis major (open circles) and latissimus dorsi (closed circles) muscles. Right column illustrates effects of additional forces caused by three of four rotator cuff muscles (supraspinatus, infraspinatus, subscapularis) for same force increments.

shrug. These individuals currently have few rehabilitation options. The following section will briefly describe a study that examined the feasibility of using FNS to provide modest but functionally significant arm movements to these individuals. The first part of this study was experimental and measured the maximum stimulated muscle forces available in a number of paralyzed shoulder and elbow muscles. The second part of the study used these forces in a model simulation based exploration of the possible functions that might be achieved through stimulation of a relatively small number of these muscles.

The force potential of several paralyzed elbow and shoulder muscles was examined in one individual with a C3 SCI. Percutaneous stimulating electrodes were implanted in anterior deltoid, middle deltoid, posterior deltoid, clavicular head of pectoralis major, sternocostal head of pectoralis major, latissimus dorsi, infraspinatus, biceps, and triceps. These muscles were cyclically stimulated for up to 8 hours per day for at least 8 weeks to increase strength and thus determine the maximum forces that might be expected in this individual. **Figure 7** summarizes the maximum elbow and shoulder moments that were measured at the end of the exercise period. It should be noted that the moments tabulated in **Figure 7** place only a lower bound on the available moments because we stimulated only a subset of the available muscles and included only one head of biceps and one of triceps.

Despite the limitations of this study, the moments elicited in this subject came very close to allowing the important function of elevating the arm through a large portion of the abduction plane. This was determined by adjusting our shoulder and elbow model to reflect an individual with a C3–level spinal cord (i.e., essentially complete paralysis of the upper limb) and then assuming that the nine muscles in the experimental study



Degree of freedom		Maximum stimulated moment (N·m)
SHOULDER	Flexion	12.91
	Extension	3.73
	Abduction	7.54
	Adduction	5.94
	Internal rotation	2.70
	External Rotation	3.59
ELBOW	Flexion	5.76
	Extension	5.25

Figure 7.
Maximum stimulated shoulder and elbow moments for an individual with a C3 SCI.

described above, with the force levels measured, were the only means available for moving the arm. A set of simulations was performed at seven arm-elevation angles in the abduction plane, evenly distributed from 30 to 120 degrees of elevation. In each of these arm positions, the inverse simulation indicated whether the available muscle set could hold the arm against gravity. With just the set of nine muscles at their measured strength, this was not possible at any arm angle. However, adding a set of stabilizing muscles (subscapularis, supraspinatus, teres minor, and serratus anterior), made it possible for the arm to be held at all elevation angles except one—when the arm was horizontal and the gravity moment in abduction was maximum. When the strength of the deltoid was then increased by 40 percent (a reasonable assumption given the limitations with percutaneous electrodes), the arm could be held at any of the tested angles. We thus believe that many individuals with high tetraplegia will benefit from a neuroprosthesis for arm movement if full recruitment of the shoulder musculature can be achieved.

DISCUSSION

Musculoskeletal modeling has the potential to significantly accelerate the development of neuroprostheses for a number of body functions, including the shoulder and elbow functions described here. Model-based simulations can be used to evaluate basic feasibility, to determine essential system details such as muscle set, and to evaluate control systems prior to implementation in human subjects. We have used musculoskeletal modeling of the shoulder and elbow to evaluate the increased function that might be provided by FNS of muscles in individuals with C5–C6 level SCI and in individuals with C1–C4 SCI. In both cases, a modest number of muscles (2 to 10, depending on SCI level) appear to be adequate to restore important functions. Simulations have also indicated that shoulder stability may be compromised by unbalanced stimulated contractions of large shoulder muscles such as the pectoralis major but also that appropriate actions of stabilizing muscles such as the rotator cuff and serratus anterior can restore the balance and maintain stability. Percutaneous stimulation of paralyzed shoulder and elbow muscles in individuals with high tetraplegia, although limited by technical constraints, indicates that sufficient strength can be provided by these muscles for simple movements.

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