Tonic-to-phasic shift of lumbo-pelvic muscle activity during 8 weeks of bed rest and 6-months follow up

Daniel L. Belavý,1,2,3 Carolyn A. Richardson,2 Stephen J. Wilson,1 Dieter Felsenberg,3 and Jörn Rittweger4

1School of Information Technology and Electrical Engineering, 2School of Health and Rehabilitation Sciences, The University of Queensland, Brisbane, Australia; 3Zentrum für Muskel-und Knochenforschung, Charité Campus Benjamin Franklin, Berlin, Germany; and 4Institute for Biophysical and Clinical Research into Human Movement, Manchester Metropolitan University, Alsager, Cheshire, United Kingdom

Submitted 2 August 2006; accepted in final form 8 February 2007

Belavý DL, Richardson CA, Wilson SJ, Felsenberg D, Rittweger J. Tonic-to-phasic shift of lumbo-pelvic muscle activity during 8 weeks of bed rest and 6-months follow up. J Appl Physiol 103: 48–54, 2007. First published February 15, 2007; doi:10.1152/japplphysiol.00850.2006.—Prior motor control studies in unloading have shown a tonic-to-phasic shift in muscle activation, particularly in the short extensors. Tonic muscle activity is considered critical for normal musculoskeletal function. The shift from tonic-to-phasic muscle activity has not been systematically studied in humans in unloading nor at the lumbo-pelvic (LP) region. Ten healthy young male subjects underwent 8 wk of bed rest with 6-mo follow up as part of the “Berlin Bed-Rest Study.” A repetitive knee movement model performed in the prone position is used to stimulate tonic holding LP muscle activity, as measured by superficial EMG. Tonic and phasic activation patterns were quantified by relative height of burst vs. baseline electromyographic linear-envelope signal components. Statistical analysis shows a shift toward greater phasic activity during bed rest and follow up (P < 0.001) with a significant interaction across muscles (P < 0.001) specifically affecting the short lumbar extensors. These changes appear unrelated to skill acquisition over time (P all ≥0.196). This change of a shift from tonic LP muscle activation to phasic is in line with prior research on the effects of reduced weight bearing on motor control.

These alterations in tonic muscle activation patterns are thought to elicit histochemical changes in the affected musculature (44). Motoneurons innervating slow muscle fibers typically fire in an ongoing (tonic) manner, whereas those innervating fast muscle fibers show phasic, on-off patterns of activity (15). Studies of cross-innervation and chronic muscle stimulation show that a change from tonic-to-phasic activation patterns in slow (type I fiber) muscle regions results in greater expression of fast (types IIa and IIb) muscle fibers (20). These findings of neuroplasticity suggest that tonic and phasic activation patterns are important in maintaining normal muscle function.

Our understanding of the effect of unloading on tonic muscle activity in humans is, however, limited. While Clément and colleagues (10, 11) found a reduction in tonic activity in soleus in humans in spaceflight, this was quantified as overall amplitude of EMG. Gross amplitude measures do not entirely characterize the degree of tonicity or phasicity of muscle contraction (compare with Refs. 2, 5, 44). A systematic study of these activation patterns has not been conducted in humans in unloading. Furthermore, the lumbo-pelvic (LP) region of the body has also been largely ignored in the unloading literature. This body region is critical in normal function, such as in load transfer between the upper and lower body (29), and can constitute a health burden for astronauts with the development of low back pain (54). In addition, dysfunction of tonic muscle activation at the LP region has been linked to low back pain (48, 49).

In this study, we wished to address this gap in the literature. We used a repetitive limb movement task to provide a continuous oscillatory, low-load input to stimulate tonic holding activity in the LP musculature. We hypothesized that a similar shift of tonic-to-phasic activation patterns will occur with long-term bed rest.

MATERIALS AND METHODS

Bed-rest protocol. The “Berlin Bed-Rest Study,” sponsored by the European Space Agency, was undertaken at the Charité Benjamin Franklin Hospital in Berlin, Germany, from February 2003 to June 2005. As part of this study, 10 male subjects underwent 8 wk of bed rest with a subsequent 6-mo follow-up recovery period. The bed-rest protocol, as well as inclusion and exclusion criteria, is discussed in detail elsewhere (45). However, in brief, horizontal bed rest was employed, although subjects were permitted to be positioned in up to
30° head-up tilt for recreational activities during daylight hours (such as watching television). Subjects performed all hygiene in the supine position and were discouraged from moving excessively or unnecessarily. Force sensors placed in the bed supports and video surveillance permitted monitoring of subjects’ activities. The institutional ethics committee approved this study and subjects gave their informed consent. Movement and testing protocol. To stimulate tonic LP muscle activity during and after bed rest, subjects conducted repetitive unilateral knee movement in a prone position (Fig. 1). This oscillatory input required the CNS to modulate ongoing activity in the LP musculature to provide a stable base for efficient knee movement. Straps were placed over the subject’s distal thigh and buttocks to reduce movement at these points and facilitate isometric LP muscle action. Movement was conducted with the right leg and a spring was attached to the right ankle to facilitate knee movement and counteract the gravitational weight of the lower leg (42, 43).

Subjects conducted right knee movement between 0 and 45° of flexion at four movement speeds (50, 75, 100, and 125 cycles/min). Three repetitions of 11 s were conducted at each movement speed. During each repetition, subjects paused their breathing to remove the influence of respiration on LP muscle activity (21). Subjects were able to view a feedback monitor through a cutout in the support apparatus. The goniometer signal was first processed to select data “regions” that targets. This process was conducted to limit the effect of extremes of performance on the observed tonic-phasic EMG patterns. This processing also provided information on movement accuracy: mean squared error (MSE) of movement speed (MSEspeed), maxima positions (MSEmax), and minima positions (MSEmin). These MSE values were calculated for each data region.

EMG signal processing. Within each data region, the relative amount of tonic and phasic muscle activity was quantified. Pilot work showed that LP muscle activity was continuous using the current repetitive-movement model. For this reason, it was inappropriate to quantify duration of on and off periods of muscle activity (as in prior work; see Refs. 2, 5, 44). Therefore, we quantified the relative amplitude of the phasic burst of EMG during the movement cycle compared with that of the underlying, ongoing tonic activation (i.e., amplitude modulation). The following algorithm was used: 1) an EMG “linear envelope” is extracted from the each 11-s EMG signal (100 Hz high-pass, 10th-order Butterworth filter, followed by full-wave rectification, and then low-pass filtering using a 10-Hz 10th-order digital Bessel filter); 2) the signal is truncated to the appropriate data region; 3) maxima and minima of the linear envelope are detected using quadratic least-squares fit; 4) the median maximum and median minimum values are calculated; and 5) calculation of the ratio of the median maximum to minimum values. We termed this ratio the “burst-tonic ratio” (BTR) representing the relative height of the phasic burst component to the underlying ongoing tonic EMG activity. With the use of this algorithm, a larger BTR value indicates more phasic muscle activity, whereas a value approaching “1” indicates more tonic muscle activation.

EMG amplitude was also quantified for use in correlation analyses with the BTR data. The root mean square (RMS) of the EMG signal in each data region was calculated. Statistical analyses. Linear mixed-effects models were employed in statistical analysis (39). ANOVA of the BTR data examined fixed effects for muscle, study date, movement speed, and all interactions up to a three-way interaction between each variable. To assess the relationship between movement accuracy and BTR, each of the

![Fig. 1. Experimental setup for repetitive knee movement. The subject was prone and able to view a monitor placed under the apparatus support. A spring was attached to the right ankle and a goniometer was placed at the right knee to monitor knee position. Straps were positioned over the buttocks and lower thigh.](image-url)
movement accuracy variables (MSE\textsubscript{speed}, MSE\textsubscript{45°}, and MSE\textsubscript{0°}) were included as linear covariates, as well as in interaction with muscle, in the statistical model. A natural log transformation of the data was applied to approximate normality. Where necessary, allowances were made for heterogeneity of variance across different grouping levels (such as movement speed or muscle).

Although goniometer signal processing excluded EMG data subsections where extremes of movement inaccuracy occurred, changes in movement accuracy within this subset of data were assessed. The goniometer MSE data from each data “region” (MSE\textsubscript{speed}, MSE\textsubscript{45°}, and MSE\textsubscript{0°}) were analyzed. Similar fixed effects of study date and movement speed were examined. A natural log transformation of the data was applied to approximate normality. The R statistical environment (version 2.0.1, www.r-project.org) was used to implement these analyses. An α of 0.05 was taken for statistical significance. As multiple measurement sessions were undertaken on the same subjects, we examined for consistent significant differences across testing days.

To examine the relationship between BTR and EMG amplitude (RMS) measures, correlation analyses were also conducted. Partial correlations for Spearman’s rank correlation coefficient (ρ), controlling for movement speed and study date were calculated and tested for significance.

RESULTS

Changes in tonic muscle activity. Table 1 gives the baseline (BRI) values of BTR for each muscle at each movement speed. Analysis of the BTR data showed significant main effects for muscle (F = 29.17, P < 0.001), study date (F = 2.38, P = 0.005), and movement speed (F = 105.38, P < 0.001). Significant two-way interactions existed for muscle\times study date (F = 1.67, P = 0.003), muscle\times movement speed (F = 13.54, P < 0.001). Additional interactions were nonsignificant (study date\times speed: F = 1.03, P = 0.415; study date\times speed\times muscle: F = 0.63, P = 0.999), implying the effect over time on each muscle was generalized across all movement speeds.

Figure 2, A and B, shows the changes in BTR for each muscle over time. The strongest effects are seen in the LES muscle group with a shift to more phasic activation patterns (increased BTR). This develops during bed rest and persists up to 6 mo afterwards (R+180). A similar trend can be seen in the TES muscle group, but only reaches significance at R+180. The IGM muscle generally shows lower BTR values during bed rest and recovery (indicating more tonic activation patterns), but this only reaches significance at the end of bed rest (BR53) and on the first testing day after reambulation (R+3). In the abdominal muscle groups, IO generally exhibited increased BTR values but this only reaches significance at one time point (R+7). The EO exhibits little change over the study period.

Movement accuracy variables (MSE\textsubscript{speed}, MSE\textsubscript{45°}, and MSE\textsubscript{0°}) were also included in the statistical model for BTR. No significant relationships existed between any of the movement accuracy variables and BTR nor in interaction with muscle (MSE\textsubscript{speed}: F = 1.25, P = 0.263; MSE\textsubscript{45°}\times muscle: F = 1.92, P = 0.102; MSE\textsubscript{45°}: F = 0.15, P = 0.699; MSE\textsubscript{45°}\times muscle: F = 1.60, P = 0.172; MSE\textsubscript{0°}: F = 1.66, P = 0.197; MSE\textsubscript{0°}\times muscle: F = 0.35, P = 0.838). These results suggest that no relationship existed between any changes in movement accuracy that may have occurred and changes in phasic-tonic EMG signal characteristics.

Movement accuracy. Table 2 shows the baseline (BRI) values of each movement accuracy variable across movement speeds. As may be expected, decreases in movement accuracy occurred with increasing movement speed (MSE\textsubscript{speed}: F = 34.40, P < 0.001; MSE\textsubscript{45°}: F = 23.37, P < 0.001; MSE\textsubscript{0°}: F = 23.02, P < 0.001; Table 2). Although extremes of movement performance were excluded from the data analyzed here, some changes in movement accuracy occurred over the course of the study (study date: MSE\textsubscript{speed}: F = 2.09, P = 0.017; MSE\textsubscript{45°}: F = 2.82, P = 0.001; and MSE\textsubscript{0°}: F = 1.99, P < 0.024), although no interactions between movement speed and study date were apparent (MSE\textsubscript{speed}: F = 1.20, P = 0.177; MSE\textsubscript{45°}: F = 0.69, P = 0.941; MSE\textsubscript{0°}: F = 0.80, P = 0.830). Figure 3 illustrates the changes in movement performance over the study period. Accuracy of movement speed (MSE\textsubscript{speed}) generally improves (MSE decreases) over the course of the study. Accuracy of movement maxima (MSE\textsubscript{45°}) does not change and movement minima accuracy (MSE\textsubscript{0°}) is actually decreased (MSE increased) at one time point, but is otherwise unchanged.

Correlation analyses. Table 3 gives the results of partial correlation analyses between EMG amplitude (RMS) and the BTR variable. As could be expected with controlling for factors such as increases in movement speed, some of the correlations are relatively weak. Importantly, however, all muscles show positive correlations between BTR and RMS. Partial correlations for the EO, IO, IGM, and LES muscle groups are all significant (P all < 0.05). In the TES muscle group, the positive correlation shows a trend to significance (P = 0.063). Overall, these results imply that more phasic EMG patterns correlates with greater EMG amplitudes.

DISCUSSION

In this study, we found a shift from tonic-to-phasic activity in the extensor musculature of the LP region in of subjects undergoing 8 wk of bed rest. This specifically affected the short lumbar extensors (lumbar erector spinae), developed during bed rest and persisted up to 6 mo afterwards. A trend existed for a similar effect in the longer thoracic erector spinae. Some changes were also seen in the internal oblique (more phasic) and IGM muscles (more tonic), although these were only just significant.

The main finding of the current study is a loss of tonic muscle activation in the erector spinae predominately affecting the short spinal extensors. Although it is unknown what muscle fiber-type changes of the spinal musculature may have occurred, magnetic resonance imaging studies of the same sub-

Table 1. Baseline (1st day of bed rest) values of quantified burst-to-tonic muscle activation

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Movement Speed, cycles/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td>External oblique</td>
<td>1.457±0.016</td>
</tr>
<tr>
<td>Internal oblique</td>
<td>1.564±0.071</td>
</tr>
<tr>
<td>Inferior gluteus maximus</td>
<td>1.360±0.041</td>
</tr>
<tr>
<td>Thoracic erector spinae</td>
<td>1.390±0.031</td>
</tr>
<tr>
<td>Lumbar erector spinae</td>
<td>1.403±0.064</td>
</tr>
</tbody>
</table>

All values are means ± SE.
jects found greatest atrophy in the short lumbar extensors (multifidus), which on average exhibit a higher proportion of type I muscle fibers (51), but less atrophy in the longer erector spinae (20a). These magnetic resonance imaging findings in the spinal extensors mirror the changes in tonic muscle activation in the current study and reflect a pattern of greater loss of tonic muscle activity (2, 5), greater fiber type changes (17), and atrophy (1, 3, 28) of the short extensors in response to unloading.

The findings are in line with prior studies of unloading. Studies of the leg musculature in animals have shown a tonic-to-phasic shift in EMG activity that effects predominately the deeper, shorter, extensors (soleus) rather than the long, superficial extensors (gastrocnemius; Refs. 2, 5). Studies of human “stance” in weightlessness (10–12) have also shown that tonic activity in the extensor (soleus) muscles is greatly reduced, although flexor (tibialis anterior) activity increases.

The observed tonic-to-phasic shift is unlikely to be due to changes in motor skill. Whereas movement speed accuracy improved over the course of the study, no significant relationships existed between any of the movement accuracy variables and the tonic-phasic EMG signal characteristics. It is, therefore, unlikely that changes in subjects’ performance of the motor task played a role in the tonic-to-phasic shift observed in the spinal extensor musculature. This cannot, however, be wholly excluded and it would be appropriate to study these EMG signal characteristics with skill acquisition.
Vestibular influences are also unlikely to be involved. Some authors suggested that the effect of the background gravitational vector on the vestibular system alters the bias to the extensor and flexor motoneuron pools of the body (e.g., 10). This is based on the findings of Magnus (31), who found a reduction in cat extensor tone when vestibular input was removed. In this study, subjects were permitted to be positioned in up to 30° head-up tilt. Although it is unknown, it can be expected that the subjects participating in the Berlin Bed-Rest Study experienced little alteration of vestibular function.

Whether changes in proprioceptive function are involved in muscle and motor control change in unloading has been debated by other authors (e.g., 41). The essential suggestion is that the deeper extensor muscles, with a greater density of muscle spindles (36, 38, 56) and slow muscle fiber (24), are more dependent on homonymous afferent input for their normal activity patterns (8, 40, 41). Afferent input has also been shown to be important in the support of tonic muscle activation and activation of slow motor units (7, 8, 47). In unloading, evidence strongly suggests that afferent muscle spindle input decreases (23, 26, 27, 37, 57). This suggests that a reduction in proprioceptive input could underlie the observed shift toward phasic activation patterns in the short lumbar extensors during bed rest and that histochemical fiber type changes may also result.

These neurophysiological studies do not, however, readily explain the effects seen in follow up. After bed rest, the tonic-to-phasic shift appears to accentuate in the extensor muscle systems. Proprioceptive input is normally thought to be restored upon reintroduction of normal gravitational load (16, 23, 26, 27). However, we observed the tonic-to-phasic shift in activation patterns to persist up to 6 mo after bed rest in the short lumbar extensors. While this could suggest that normal proprioceptive input was not restored, the underlying mechanisms are unclear.

Although repeatability of EMG measurements has been established for periods of up to 1 wk (13), there is a paucity of data with regards to longer time periods. However, the changes in motor control that were observed in the current study were generally consistent in both direction and magnitude, with progressive changes over time. No large alterations in direction or magnitude of the observed tonic muscle activation patterns occur from one testing day to the next. Thus repeatability, or lack thereof, does not present a significant problem for the findings of the current study.

One of the potential implications of these motor control changes is a loss of tonic activation for LP stabilization. Past work has suggested tonic muscle activation to be important for stabilizing LP joint structures (49). Findings in low back pain have shown a loss of tonic muscle activation, particularly in the deep musculature (22, 48). The findings of a tonic-to-phasic
shift, particularly in the short lumbar extensors, could also imply a loss of the tonic holding/stiffening capacity of this muscle. Additional work is, however, necessary to examine any potential link between this shift to phasic muscle activation and actual risks of tissue injury.

In summary, we investigated the response of tonic activation patterns in superficial LP muscles of human subjects to 8-wk bed rest with subsequent 6-mo follow up. We found a shift of tonic-to-phasic muscle activation that affected predominantly the short lumbar extensors. Changes in motor skill and vestibular function are unlikely to be the cause for these changes, and prior research favors the opinion that alterations in proprioceptive function and reduction in normal weight bearing may underlie the observed motor control changes.

ACKNOWLEDGMENTS

The authors thank Benny Elmann-Larsen of the European Space Agency, the subjects who participated in the study, and the staff of ward 18A in the Charité Campus Benjamin Franklin Hospital, Berlin, Germany. Dr. Björn Bühring und Dr. Franzki Luhn are also thanked for their support for the duration of the study.

GRANTS

The Berlin Bed-Rest Study was supported by Grant 14431/02/NL/SH2 from the European Space Agency.

REFERENCES


