Resistance training enhances the stability of sensorimotor coordination

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Strategies for the control of human movement are constrained by the neuroanatomical characteristics of the motor system. In particular, there is evidence that the capacity of muscles for producing force has a strong influence on the stability of coordination in certain movement tasks. In the present experiment, our aim was to determine whether physiological adaptations that cause relatively long-lasting changes in the ability of muscles to produce force can influence the stability of coordination in a systematic manner. We assessed the effects of resistance training on the performance of a difficult coordination task that required participants to synchronize or syncopate movements of their index finger with an auditory metronome. Our results revealed that training that increased isometric finger strength also enhanced the stability of movement coordination. These changes were accompanied by alterations in muscle recruitment patterns. In particular, the trained muscles were recruited in a more consistent fashion following the programme of resistance training. These results indicate that resistance training produces functional adaptations of the neuroanatomical constraints that underlie the control of voluntary movement.

Keywords: strength training; neural adaptations; coordination; finger movements

1. INTRODUCTION

It is now well established that many of the functional characteristics of neurobiological systems are captured succinctly by abstract dynamical laws (e.g. Golubitsky *et al.* 1999), yet the relationships between these abstract laws and the biological structures that are ultimately responsible for generating behaviour remain largely unresolved. It has been demonstrated in the field of movement science that the time-course of brain activation is very different for tasks involving synchronization (actions on the beat of a pacing signal) and syncopation (actions between the beats of a pacing signal) (Kelso *et al.* 1998). In so much as the primary features of the cortical dynamics are preserved, regardless of whether the act of coordination requires flexion or extension movements, global patterns of brain activity appear to express the operation of rather abstract constraints.

Other studies have demonstrated that the neuroanatomical characteristics of the muscles and joints involved in a task have a profound influence on the stability of coordination. Tasks that involve synchronization of a finger flexion movement with a pacing signal are performed in a more consistent fashion than those that require a finger extension movement to be made in time with the signal. Furthermore, if the frequency of movement is steadily increased, transitions from the extend-on-the-beat pattern to the flex-on-the-beat pattern are typically observed (Carson 1996). The muscles that act in order to flex the finger are stronger and exhibit higher gain than the extensors. As a consequence, a smaller proportion of flexor motor units need to be activated in order to produce a given level of force (Vallbo & Wessberg 1993) and a greater modification in flexion torque occurs for a unit change in cortico-motoneuronal cell

activity (Cheney *et al.* 1991). It has also been shown that changes in the posture of the wrist that result in alterations in the lengths and orientations of the extrinsic finger muscles have both predictable and reliable effects on the stability of the extend-on-the-beat pattern of coordination (Carson & Riek 1998). These data suggest that the stability of coordination is strongly influenced by the force-generating capacity of the muscles engaged during the task.

The purpose of the present study was to assess the impact of resistance training on the performance and control of a difficult coordination task. Our aim was to determine whether physiological adaptations within the neuromuscular system that lead to relatively long-lasting changes in the capacity of muscles for generating force exert a predictable influence on the stability of coordination. In addition to assessing the behavioural consequences of resistance training, electromyographic (EMG) recordings were obtained from the primary muscles engaged in the task in an effort to identify potential changes in how these muscles were recruited by the central nervous system following training.

2. METHODS

(a) *Participants*

Sixteen healthy, adult volunteers (aged 18–32 years) participated in this experiment. Eleven participants were randomly assigned to either a control ($n = 5$, two females and three males) or a resistance training ($n = 6$, three males and three females) group. Five individuals (three females and two males) were subsequently recruited to an additional training condition involving unresisted movement. All participants with the exception of one male in the resistance training group were right handed (Oldfield 1971). Each individual gave informed consent to the procedures, which were approved by the University of Queensland Medical Research Ethics Committee.

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(b) Procedure

This experiment was designed to determine the influence of resistance training upon the performance of a coordination task characterized by rhythmic flexion–extension movements of the index finger. The coordination task was performed before and after a four-week training period. During the training period, participants in the two training groups completed 12 training sessions involving flexion–extension movements of the index finger. Loads were applied to the movements performed by the resistance training group such that the extension phase of the movements was resisted. Participants in the unresisted training group moved against no resistance other than the weight of their finger. Control participants did not train.

(c) Coordination task

In the coordination task, the participants were required to synchronize (coordinate movements ‘on the beat’) or syncopate (coordinate movements ‘between the beats’) either flexion or extension of their right index finger with the beat of an auditory metronome. Ten trials were performed in each of four patterns: extend-on-the-beat, flex-on-the-beat, extend-between-the-beats and flex-between-the-beats. The 40 trials were performed in a random order that was held constant for each person across experimental sessions. The participants were seated beside a table upon which their right forearm and hand were supported in a neutral position. A plastic splint was secured on the dorsal and ventral surfaces of the index finger in order to prevent motion at the interphalangeal joints. The thumb and remaining fingers were secured in a flexed position around a wooden cylinder. The displacement of the index finger was obtained via a potentiometer that was aligned coaxially with the metacarpal–phalangeal joint and attached to the finger via a metal shaft (figure 1a). A loudspeaker presented auditory signals (500 Hz square wave) at a rate that was incremented by 0.25 Hz every 8 s. The duration of each trial was 66 s and consisted of eight isofrequency plateaus. If the participants could successfully perform the four coordination patterns at 1.25 Hz during practice trials, the initial pacing frequency was set at 1.25 Hz. If any of the coordination patterns could not be performed at 1.25 Hz, the initial pacing frequency was set at 0.75 Hz.

In the flex-on-the-beat and extend-on-the-beat (synchronization) conditions, the participants were instructed to coordinate maximum angular displacement with the beat of the metronome in the direction of finger flexion and extension, respectively. In the flex-between-the-beats and extend-between-the-beats (syncopation) conditions, the participants were instructed to move their fingers so that the maximum angular displacement occurred at the point in time midway between the two metronome beats in the direction of finger flexion and extension, respectively. The participants were instructed that their primary aim was to maintain their movements in the prescribed pattern of coordination at the frequency dictated by the metronome. Secondary to this, they were asked to maintain a movement amplitude that was as large as possible throughout the trial. The participants were instructed not to intervene if the pattern they were performing changed, but to maintain the prescribed frequency and adopt whatever pattern emerged naturally (Kelso 1984). Since the patterns that required participants to syncopate their movements with the metronome could potentially be achieved by adopting a strategy for synchronizing the opposite direction of movement with the beat (Kelso *et al.* 1990), subjects were repeatedly reminded to conceptualize the task according to the designated strategy.

Figure 1. (a) The experimental set-up for the coordination task. (i) The finger splint, (ii) the potentiometer and rotating shaft, (iii) the active electrode site for the EDC muscle, (iv) the active electrode site for the FDI muscle, and (v) the active electrode site for the FDS muscle. (b) The resistance training device.

(d) Electromyographic recordings

The EMG activities of the first dorsal interosseus (FDI), flexor digitorum superficialis (FDS) and extensor digitorum communis (EDC) muscles were recorded with fine wire electrodes during the coordination task for the resistance training and control groups. Each bipolar electrode consisted of a single strand of 75 μ m diameter stainless steel wire and a disposable 10 mm diameter Ag/AgCl electrode attached to the skin above a bony prominence. The fine wire was insulated with Teflon, except for 2–3 mm sections that were bared at either end and inserted into the muscle with a 27 gauge hypodermic needle. The signals were band-pass filtered (30 Hz–1 kHz), amplified, digitized at a sampling rate of 2 kHz and stored to disk.

(e) Training programme

Resistance training was performed on a custom-built device that restricted movement to rotation about the second metacarpal–phalangeal joint (figure 1b). Flexion of the interphalangeal joints of the index finger was prevented with a thermoplastic splint. The second metacarpal–phalangeal joint was aligned coaxially with a pulley to which weights were attached in a manner that applied a resistance to extension movements at a point 5 cm from the axis of rotation.

A potentiometer was attached in series to the main shaft of the training device in order to record the joint position during training. The calibrated output of the potentiometer was amplified and displayed in real time in order to provide visual feedback to the participants. They were required to lower and raise their fingers between 25 and 70° of finger flexion in time with

an auditory pacing signal (0.7 Hz). The average power of the training movements relative to maximal strength was therefore similar for all of the participants. Four trials, each consisting of six complete finger flexion–extension cycles, were completed in each training session. All training loads were scaled to each individual's maximal dynamic strength; the load was increased from 70% of maximum in steps of 5% whenever three sessions had been completed with the previous load. Participants in the unresisted training group performed the same number of movements at the same movement frequency against no resistance other than the weight of their finger.

(f) Strength testing

The resistance training device was also used to assess the maximal isometric index finger flexion and extension strength before and after the training period. A torque transducer was attached coaxially to the pulley such that static flexion and extension torques about the second metacarpal–phalangeal joint were measured at 45° of finger flexion. Two trials of 5 s were conducted in each direction. Participants were instructed to increase torque for 2 s and to then exert maximal torque for the remaining 3 s. Verbal encouragement and visual feedback of performance were provided.

(g) Data reduction

In order to assess the performance of the coordination task, we first calculated the relative phase relation between the metronome signal and points of peak flexion (for the flex-on-the-beat and flex-between-the-beats trials) and peak extension (for the extend-on-the-beat and extend-between-the-beats trials). A custom peak picking routine was used to identify the time of peak deceleration of the finger as it approached full extension and flexion during each movement cycle. The point of peak deceleration was a reliable estimate of the time at which the finger first approached its maximum displacement. The primary measure of the stability of coordination was the length of time that the required relative phase relation could be successfully maintained. The point of departure from the initial coordination pattern was determined using standard procedures (e.g. Carson 1996). Briefly, relative phase profiles were inspected via a graphical interface in order to detect the first period, of greater than 3 s duration, during which the relative phase relation departed from the expected value (i.e. in-phase with the metronome = 0° and anti-phase with the metronome = $\pm 180^\circ$) by more than 60°. Cursors were positioned at either end of the region prior to departure from the expected relative phase angle and at either end of the region after, during which a new stable phase relation was established. The mean relative phase was calculated for the pre- and post-transition regions defined by these cursor positions. If a stable pattern did not emerge following departure from the initial pattern (i.e. phase wandering), the post-transition mean was assigned a value of 180° plus or minus the expected relative phase angle of the pre-transition pattern. The relative phase angle midway between the pre- and post-transition means was calculated and a linear regression was calculated for the relative phase data about this point (figure 2). The onset and offset of the transition were defined as the points at which the regression function intersected with the pre- and post-transition means.

In order to detect transitions from between-the-beats patterns to on-the-beat patterns, which are described by an identical relative phase relation (i.e. flex-between-the-beats to extend-on-the-beat and extend-between-the-beats to flex-on-the-beat

Figure 2. Raw and processed data collected during the coordination task. (a) The timing of the metronome pulses, raw position data and the discrete relative phase relation between the metronome and the finger position. The figure depicts a transition in pattern from extend-between-the-beats to extend-on-the-beat. The pre-transition mean relative phase was calculated from a section of the file of much greater duration than is displayed. The onset of the transition was determined as the point at which a linear regression fitted to the relative phase relation at the midpoint between the pre- and post-transition means intersected with the pre-transition mean. (b) The timing of the metronome pulses, raw EMG data and enveloped EMG data (full-wave rectified and low-pass filtered at 6 Hz). The coordination pattern is extend-on-the-beat and the section of the trial is taken from a pre-transition period. The onset of each EMG burst is illustrated in the raw data trace. The enveloped EMG signal was used to calculate the autocorrelation function.

patterns), the first derivative of the raw displacement was inspected. In the flex- and extend-on-the-beat patterns it was evident that the peak angular velocity of the finger as it approached the point of synchronization was always greater than the peak velocity in the opposite direction. Instances in which the angular velocity of the finger was greater as it moved away from the nominated direction of syncopation were therefore indicative of a change in pattern. Transition onsets were determined to be the first of at least three consecutive movement cycles, for which the peak angular velocity in the direction away from the nominated direction of syncopation was greater than

the peak velocity in the nominated direction by at least 10% of the peak angular velocity during the entire trial.

All subsequent kinematic and EMG data analyses were performed only on the portion of the trials during which the initial target pattern was successfully maintained. The circular variance of the relative phase relation between the finger and the pacing signal (uniformity) was employed as an additional measure of the stability of coordination. Uniformity is a measure of angular dispersion and was calculated according to Mardia (1972). It is the directional equivalent of the ordinary standard deviation and takes values in the range 0–1. A value of 1 indicates that all of the angles in the sample are equal and a value of 0 indicates that the angles are homogeneously distributed in the range 0– 2π . Uniformity values approaching 1 therefore indicate a stable relation between the finger and the pacing signal whereas values near zero describe variable relative phase relations.

The EMG signals were full-wave rectified and low-pass filtered at 6 Hz (Winter 1990). An autocorrelation function was calculated for each EMG time-series. The highest coefficient outside the central peak at lag 0 was taken as a measure of the spatial and temporal regularity of muscle activation. This value typically occurred at a lag equivalent to the period of the movement due to the bias towards more central lags associated with time-series of finite length (Challis & Kitney 1990). The magnitude of the peak autocorrelation coefficient therefore indicated the degree of coherence between the original EMG trace and the same trace when shifted in time by one movement cycle. The measure reflected the degree of similarity between each EMG burst and the next in terms of length, magnitude and shape, as well as consistency in the timing of the bursts. Due to the relative selectivity of fine-wire EMG signals to a restricted proportion of the motor units within a muscle, some trials included periods of limited EMG activity. This usually occurred for relatively short periods within trials that otherwise contained a clearly defined, phasic EMG signal with a good signal to noise ratio. A threshold correlation coefficient of 0.45 was set for inclusion in further analyses in order to exclude trials containing periods of limited EMG signal. On this basis, a similar number of trials were rejected before and after training (pre=145 (33%) and post=118 (27%)). The exclusion procedure was considered to be a conservative measure because, even if some trials with genuinely irregular EMG signals were rejected from the analysis, this would serve to reduce the magnitude of effects from pre- to post-training. The EMG burst onsets were identified using custom routines that determined the first point in each burst at which the rectified and enveloped EMG signal exceeded the mean level of baseline EMG signal by three standard deviations. The coefficient of variation of the periods between burst onsets was calculated in order to provide a direct indication of the temporal regularity of the muscle activity. In order to obtain coefficients that were not biased by occasional occurrences where the burst detection algorithm failed to detect an onset for a particular burst or detected more than one onset within the same burst, only periods between EMG burst onsets that were less than twice the metronome period and greater than half the metronome period were included in the calculations.

3. RESULTS

All of the participants could successfully perform each of the four patterns of coordination at low frequencies of

movement. However, as the frequency of the pacing signal was increased the stability of coordination decreased markedly. In many cases, spontaneous transitions from less stable to more stable patterns occurred. Prior to training, it was evident that the required movement pattern had a profound impact on the stability of coordination (Page test for ordered alternatives, $p < 0.05$). Patterns involving synchronization with the metronome could be sustained at higher frequencies than those requiring syncopation with the metronome and patterns involving coordination of finger flexion with the pacing signal were maintained longer than the corresponding patterns that required finger extension to be coordinated with the metronome (median time to transition, extend-between = 27 s, flex-between = 34 s, extend-on = 63 s and flex-on = 66 s).

The isometric strength of the index finger extensors (pre = 0.62 Nm and post = 0.78 Nm) ($p < 0.05$) and flexors (pre = 3.99 Nm and post = 4.49 Nm) ($p < 0.05$) increased in response to resistance training. There were no statistically significant changes in strength following training involving unresisted movements, nor in response to repeated exposure to the testing procedures.

Resistance training resulted in an increase in the stability of the extend-between-the-beats pattern of coordination, as indicated by an increase in the median duration of successful execution of the pattern from 26.95 s prior to training to 34.50 s following training ($p < 0.05$). No other statistically significant changes in the times to transition were evident (figure 3). The stability of coordination in the period prior to the transitions was also enhanced by resistance training in both the flex-between-the-beats and extend-on-the-beats patterns ($p < 0.05$) (figure 4). These increases in uniformity were large (flex-between effect size $f = 0.85$ and extend-on effect size $f = 0.59$). Moderate to large increases in movement consistency occurred in some cases for the unresisted training group (extend-between effect size $f = 0.51$) and the control group (extend-on effect size $f = 0.53$) ($p < 0.05$). These results indicate that, while repeated exposure to the task and unresisted training did not extend the period of time that the patterns could be performed, in some instances these interventions increased the stability of coordination in the period prior to transitions.

The EMG activity of the primary muscles engaged in the coordination task was analysed in order to determine whether changes occurred in the manner in which these muscles were recruited. It was clearly apparent that the muscles that were the target of the resistance training programme were recruited in a more consistent fashion following training. The peak coefficients of the autocorrelation of the extensor muscle EMG signal increased markedly after resistance training during performance of the extend-on-the-beats and extend-between-the-beats coordination patterns ($p < 0.05$) (extend-on effect size $f = 1.03$ and extend-between effect size $f = 1.39$) (figure 5). There were no statistically significant changes in EMG consistency for the flex-on-the-beat ($f = 0.48$) or flex-between-the-beats ($f = 0.52$) patterns, despite moderate to large effects. Following resistance training, the variability of the periods between extensor muscle EMG burst onsets decreased significantly for the extend-on-the-beats condition ($p < 0.05$ and $f = 0.95$)

Figure 3. Median times to transition for the three experimental groups in the four coordination patterns: (a) extend-between-the-beats, (b) extend-on-the-beat, (c) flex-between-the-beats, and (d) flex-on-the-beat. The external error bars extend from the tenth to the 90th percentiles of the range, the boxes span the interquartile range, the horizontal bar within each box identifies the median and the solid dot shows the mean. Each pattern is depicted by a schematic below the appropriate panel. Times to transition from before the training period are represented by shaded boxes and from after the training period by open boxes. Stars represent a statistically significant change from pre- to post-training.

but not for the extend-between-the-beats pattern. Thus, while a more regular timing of extensor muscle activation occurred in the extend-on-the-beats pattern, an increase in the spatio-temporal regularity of the EMG bursts was apparent in the extend-between-the-beats pattern and, to some extent, in the extend-on-the-beats pattern following training.

The control group did not exhibit statistically significant changes in the regularity of muscle activity. Those alterations that were observed, although associated with large effect sizes (flex-on effect size $f=0.74$ and extend-on effect size $f=0.81$), were considerably smaller than the statistically significant changes that were evident for the resistance training group. There were no statistically significant changes in the patterns of muscle activation of either the flexor or FDI muscles.

4. DISCUSSION

Our findings clearly demonstrate that resistance training that increases muscular strength also increases the stability of coordination. Improvements in task

Figure 4. Mean uniformity of the relative phase relation between the metronome and the finger displacement for the three experimental groups in the four coordination patterns: (a) extend-between-the-beats, (b) extend-on-the-beat, (c) flex-between-the-beats, and (d) flex-on-the-beat. Each pattern is depicted by a schematic below the appropriate panel. Uniformity values from before the training period are represented by shaded boxes and from after the training period by open boxes. Stars represent a statistically significant change from pre- to post-training.

performance were accompanied by changes in the pattern of recruitment of the muscles that were the focus of the resistance training programme. Specifically, the trained muscles were recruited in a more consistent fashion after training. These findings suggest that resistance training is associated with changes in the nature of the neuro-anatomical constraints underlying the control of voluntary movement.

Resistance training led to an increase in the ability of the finger muscles to generate force. Therefore, following training a reduced level of central drive would have been required in order to generate an equivalent behavioural outcome. It has been proposed that the potential for interference between functionally proximal areas of the cerebral cortex increases with the degree to which these areas are activated (Kinsbourne & Hicks 1978). A reduction in the level of central drive required to perform the coordination task may therefore have enhanced the stability of coordination by reducing the degree of interference between the motor centres engaged in the task.

It is likely that modifications to structures located at many points in the motor pathway underlie changes in the efficacy of the descending command. An obvious candidate is an increase in the intrinsic ability of the muscle fibres in the trained muscles to generate force. If each motor unit within a muscle is capable of producing more force, it follows that fewer motoneurons need to be recruited in order to produce an equivalent kinetic or kinematic outcome. Thus, resistance training could have

Figure 5. Mean autocorrelation coefficients for the EMG time-series of the control and resistance training groups in the four coordination patterns: (a) extend-between-the-beats, (b) extend-on-the-beat, (c) flex-between-the-beats, and (d) flex-on-the-beat. Each pattern is depicted by a schematic below the appropriate panel. Autocorrelation coefficients from before the training period are represented by shaded boxes and from after the training period by open boxes. Stars represent a statistically significant change from pre- to post-training.

enhanced performance in the coordination task by reducing the number of extensor muscle motor units that needed to be recruited in each movement cycle. This would have led to a reduction in the required level of central drive to the extensor motoneurons.

Although it is plausible that the changes in muscular strength observed arose as a consequence of adaptations within the trained muscles, it is widely accepted that substantial muscular adaptations do not occur until several weeks after the beginning of a resistance training programme (e.g. Moritani 1993; Enoka 1997). Estimates of the period of training required to induce changes such as muscle hypertrophy and alterations in the ratio of muscle fibre types vary between three and eight weeks (Sale 1988; Moritani 1993; Enoka 1997). The weight of available evidence suggests that most of the increases in strength in the initial stages of resistance training are due to adaptations within the central nervous system.

Adaptations to a number of structures along the motor pathway prior to the neuromuscular junction could act to increase the efficiency of the central command. It is clear that the synaptic effectiveness of neural connections between areas within the primary motor cortex can be modified through physical activity (Classen *et al.* 1998; Cohen *et al.* 1998). Imaging studies have also identified changes in the extent of activity within secondary motor areas during the process of learning tasks that involve sequences of movements (Friston *et al.* 1992; Jenkins *et al.*

1994; Schlaug *et al.* 1994). Although to date there have been no experiments conducted that have directly assessed whether resistance training is associated with cortical adaptations, it is apparent that our findings could be explained by plasticity in the motor cortex that led to a reduction in the required level of drive from areas 'upstream' of the motor cortex (cf. Gandevia *et al.* 1996). At a segmental level, activity-related changes in the number or strength of connections between alpha motoneurons and descending or afferent fibres may also reduce the amount of descending drive required to perform a task. The motoneuron itself is a potential site of adaptation. In this regard, Carp & Wolpaw (1994) presented evidence that the activation threshold of alpha motoneurons can be altered in primates through operant conditioning. The time-course of supra-spinal plasticity cited in this section ranged between a few minutes and a number of days. Few experiments have reported plasticity at segmental levels following training of shorter duration than five weeks (see Wolpaw (1997), for a review). For example, Wolf *et al.* (1995) found that spinal stretch reflexes were modified by five weeks of operant conditioning. The duration of Wolf *et al.*'s (1995) experiment is comparable to the four-week duration of the present experiment. In combination, the evidence regarding the time-course of neural plasticity associated with learning is consistent with the interpretation that changes in coordination stability following resistance training are due to adaptations within the central nervous system.

In summary, our findings demonstrate that coordination is governed by both abstract constraints, such as those that give rise to the greater stability of synchronization over syncopation patterns, and neuroanatomical constraints, such as those expressed in the greater stability of coordination patterns requiring flexion rather than extension movements. Resistance training leads to adaptive and functionally specific alterations of the neuroanatomical constraints underlying the control of voluntary movement and, thereby, directly impacts upon the stability of sensorimotor coordination. What remain to be determined are the precise sites of adaptation along the motor pathway that give rise to such profound changes in neuromuscular control.

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