Changes in Neural Modulation and Motor Control During Voluntary Movement of Older Individuals

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Background. Changes in the modulation of soleus alpha motoneuron excitability, as assessed by H-reflexes, and temporal sequencing of the soleus and tibialis anterior muscles during voluntary ankle dorsiflexions and plantar flexions of young (24.7 ± 11.5; n = 13) and older (68.7 ± 5.4; n = 13) subjects were assessed to determine potential neural mechanisms that might contribute to motor control changes associated with aging.

Methods. A repetitive stimulation (5 Hz) soleus H-reflex testing protocol and surface electromyography (EMG) were used to assess the latencies of soleus H-reflex changes in relation to tibialis anterior and soleus EMG activations of standing subjects during voluntary ankle dorsiflexions and plantar flexions at self-selected speeds. The pattern and latency of H-reflex changes in relation to EMG activity were compared between young and old subjects.

Results. There were no differences in the relative amount of antagonist muscle (soleus) inhibition during voluntary ankle dorsiflexions between young and old subjects (26.4% and 27.2% decrease from resting H-reflex values, respectively). Older subjects, however, required additional time to achieve these levels of inhibition. Delays in the activation of soleus H-reflexes during the plantar flexion task were also observed in older subjects. Older subjects also had considerable intra- and intersubject variability in muscle temporal sequencing patterns during ankle plantar flexions.

Conclusions. Although older subjects exhibited similar relative levels of alpha motoneuron inhibition and excitation during voluntary movements, this modulation was delayed when compared to younger subjects. Temporal sequencing of muscle activations also appears to undergo change with aging.

OLDER individuals experience motor control changes with increasing age (1,2). To date, physiological studies of the effects of aging on mobility have focused primarily on muscular and peripheral neuromuscular changes (3,4) or reactions to postural perturbations (5,6). Few studies have examined potential changes within the central nervous system during voluntary movements of older individuals (7,8). Little is known of the central control of anticipatory responses that precede muscle activity during a voluntary movement.

Anticipatory postural responses precede voluntary movement and compensate for any potential destabilization. Temporal sequencing of muscle activity during anticipatory and voluntary movements appears to be a learned task that is centrally organized. The movement deficits associated with aging have led to speculation that perhaps there is an alteration in the coordination between anticipatory and voluntary movements that is of central origin (1,9).

Thus far, the speculation has been based primarily on examining differences in surface electromyographic (EMG) recordings between young and old subjects. Although valuable, surface EMG studies cannot differentiate between changes occurring centrally from those occurring peripherally. Physiological studies that have examined movement deficits associated with aging have focused on the increase in the amount of time needed for a muscle twitch to achieve peak force (3,10,11), sensorimotor deficits (12), and decreases in nerve conduction velocity (10). We are unaware of any studies that have examined central changes during self-initiated (i.e., not a reaction-time task), unrestrained movements at self-selected speeds. Studies using the H-reflex were therefore initiated to examine this issue.

The H-reflex is an indirect measure of the excitability of the alpha motoneuron pool and reflects changes in the convergent peripheral and central neural input to this pool. H-reflex methodologies have been used to assess changes in human motoneuron excitability during voluntary movements (8,13–15). It has proven to be a valuable tool in assessing modulations associated with normal movement and in identifying changes associated with pathology and neural dysfunction (16–18).

The present study examined changes in soleus alpha motoneuron excitability, via H-reflex testing, during voluntary ankle dorsiflexions and plantar flexions at self-selected speeds of standing young and old subjects. The methodology used permitted the examination of changes during the execution of the movement and during the anticipatory reactions that preceded these movements. Changes in the temporal sequencing of muscle activity between two antagonists [soleus and tibialis anterior (TA muscles)] were correlated to changes in soleus alpha motoneuron excitability to determine whether there were any variations that were associated with aging. Preliminary results have been published in abstract form (19).
METHODS

Subjects

Twenty-eight subjects volunteered for participation in this study following informed consent. Data from two older subjects were not included in statistical analyses either because they were unable to maintain stable M-wave recordings, or a sufficient number of recordings that fit our inclusion parameters were not obtained. Data were analyzed from 13 healthy, nondisabled elderly subjects (M age = 68.7 ± 5.4; range = 56–78 years; 7 male, 6 female) and 13 younger, nondisabled subjects (M = 24.7 ± 11.5; range = 16–45 years; 7 male, 6 female). To be included in the study, subjects had to be free of neurological or orthopedic impairments. Subjects were independent ambulators, without artificial joint replacements, and without a history of increased incidence of falls, headaches, double vision, or balance disorders. This information was obtained by self-report and a brief physical examination. All experiments received prior approval of The University of Montana Institutional Review Board for the Use of Human Subjects and were performed in accordance with the 1964 Declaration of Helsinki.

EMG Recording and H-Reflex Stimulation Procedures

Testing consisted of the recording of soleus H reflexes and surface EMG recordings of the soleus and TA muscles during voluntary dorsiflexion and plantar flexion of the ankle. Subjects were prepared for H-reflex testing and EMG recordings in the following manner. Bipolar surface electrodes (1.6 mm silver-silver chloride; 2 cm between active sites) were applied to the skin overlying the soleus and TA muscles. Soleus H reflexes were elicited by stimulating the posterior tibial nerve. Stimulation was provided by a somatosensory stimulator (model S10DSMC, Grass, West Warwick, RI). The anode electrode for the test stimulus was placed proximal to the patella. The stimulating electrode was placed in the popliteal fossa after the optimal position for stimulation of the posterior tibial nerve was determined. A maximum M wave was determined. To standardize among subjects the percentage of the motoneuron pool being stimulated during testing procedures, stimulus intensity was adjusted to give an H reflex within the initial “plateau region” of the H-reflex recruitment curve (i.e., between the ascending and descending portion of the curve). Within this region, H-reflex amplitudes remain stable despite substantial changes in M responses (20,21). If a maximal M-wave recording was not possible because of subject sensitivity to electrical stimulation, or if it was not possible to elicit an H reflex that was 25% of a maximal M wave, then an H-reflex amplitude that was approximately 50% of a maximal elicited H response was used as the resting value. Soleus and TA EMGs were recorded simultaneously and digitized at a sampling rate of 2 kHz with a 12-bit analog-to-digital converter (TEAC-Intelligent, Tokyo, Japan) interfaced with the computer (Hewlett-Packard Vectra 320, San Jose, CA).

With the subjects in a standing position, the posterior tibial nerve was repetitively stimulated (5 Hz) using a rectangular wave pulse of 0.5-ms duration. H-reflex responses and TA and soleus EMGs were monitored online with a 20-MHz digital storage oscilloscope (Hitachi VC-6020, Tokyo, Japan). Online analysis allowed determination of H-reflex and M-wave stability prior to data collection initiation. Details of necessary controls and benefits of using repetitive rather than single-stimulation H-reflex procedures have been described elsewhere (21,22).

Experimental Procedures

Subjects stood with weight equally distributed on both legs, arms held comfortably at their sides, with eyes fixated on a stationary target. The computer was manually triggered to begin a 2-s trial of data collection once the following criteria were met: (a) a stabilized soleus H-reflex response, (b) quiescence of soleus and TA muscle activity (except for trials where a forward body position was used to elicit increased soleus EMG activity), and (c) no noticeable changes, during visual observation of subjects, in extraneous movements of the body. Following initiation of each trial, and with variable time delay, the subjects were verbally instructed to dorsiflex or plantar flex the ankle, at a speed that was comfortable to them, and to maintain that position until the trial was completed. Instructions to dorsiflex or plantar flex the ankle were also pseudo-randomized to minimize subject anticipation and adaptation of responses. Subjects were occasionally asked to lean forward to provide for various amounts of background soleus EMG activity. This ensured that H-reflex recordings were obtained over a range of resting background EMG levels and H-reflex modulations were independent of background EMG levels. Testing continued until 10 acceptable trials were obtained from each subject for each condition (dorsiflexion and plantar flexion). Two seconds of data with a 5-Hz stimulation rate yielded 100 H-reflex and M-wave recordings per subject per condition. In this manner, multiple H-reflex and EMG recordings could be obtained during restful standing as well as preceding, during, and following the movement. Interspersed among movement trials were trials in which no command to move was given. This was to ensure that no modulations of the H reflex or M wave occurred during the 2-s trials secondary solely to the repetitive stimulations.

H Reflex and Statistical Analysis Procedures

To control for normal variations in resting H values, the H amplitude (peak-to-peak) of each subject was standardized. The single maximum soleus H-reflex amplitude recorded (in mV) from each individual subject, during each condition (i.e., dorsiflexion or plantar flexion), during 10 trials was set to 100%. All absolute values were then computed as percentages of this value. Subject data were then pooled, thus allowing comparison between groups. Changes in H-reflex amplitudes were analyzed in relation to onset of EMG activity of the TA for dorsiflexion and soleus muscle EMG activity for plantar flexion. Onset of EMG activity was determined by a computer program that identified onset as a signal that was 10% above baseline values and maintained for greater than 250 ms. EMG signals were rectified and high-pass filtered at 20 Hz. For statistical analysis, H-reflex amplitude data were divided into 50-ms bins in relation to the onset of TA or soleus EMG activity (e.g., 0–50 ms prior to TA EMG onset; 0–50 ms...
post-TA EMG onset) (see Figures 1 and 2). Each bin contained no fewer than 25 H-reflex amplitude recordings.

M-wave responses were collected concurrently with H-reflex recordings. M-wave variability was kept to a minimum by adjusting stimulus intensity between trials if necessary. For instance, subtle, undetected changes in limb position or stimulating electrode movement can affect M-wave amplitudes. Changes were detected by visual observation of M and H waves on the oscilloscope. Keeping resting M waves constant ensured that the same percentage of the motoneuron pool was stimulated from trial to trial. M-wave variation was assessed off-line using analysis of variance (ANOVA).

Computerized data processing and analysis procedures have been described in detail elsewhere (22,23). H-reflex amplitudes and M-wave amplitudes were statistically analyzed. Statistical analyses included mean, standard deviation, and ANOVA with a Tukey post-hoc analysis for statistical inference; p-values <.05 were considered significant. A Pearson correlation analysis was used to determine whether or not there were any correlations between H-reflex and M-wave changes.

Data analysis revealed considerable intersubject variability in muscle activation patterns between the TA and soleus muscles of older subjects. Different muscle activation patterns will affect H reflexes differently. Therefore, only those trials in which the muscle activation pattern was similar to younger subjects were used for group H-reflex analysis. If a subject had fewer than five acceptable trials, they were not included in the statistical analysis.

RESULTS

M-Wave Analysis

For the dorsiflexion condition, M-wave amplitudes were relatively constant (<8% variability from -200 to +200 ms pre- and post-TA EMG onset) and H-reflex amplitudes varied independently of M-wave amplitudes. During the plantar flexion task, M waves remained constant prior to movement and 50 ms post-soleus activation, but increased a nonsignificant 12% in young subjects (p = .641) and 23% in older subjects (p = .059) 51–100 ms after movement initiation. Plantar flexion bins 7 and 8 (representing recordings 101–200 ms post-soleus EMG onset) of older subjects differed significantly from pre-activation M-wave amplitudes (p-value ranges .001–.032). The greater increase in the older subjects was probably secondary to slight straightening of the leg during plantar flexion. This increase in M waves after movement initiation could not account for H-reflex changes occurring prior to this time and thus were inconsequential to these results. Changes in H-reflex amplitudes were compared to changes in M-wave amplitudes using Pearson correlation analysis. Values ranged from -1.14 (all recordings) to -.039 (recordings made subsequent to movement), thus indicating essentially no correlation between changes in H and M amplitudes.

Subjects 16–45 Years of Age

Voluntary dorsiflexion. — Soleus H-reflex amplitudes decreased 22.2% prior to the onset of TA muscle EMG activation (Figure 1A). The decrease occurred 50 ms or less before TA muscle activation. This represents a significant decrease (p = .018) from the immediately preceding bin containing recordings from 100 to 51 ms prior to TA activation. Immediately following TA activation (0–50 ms post-TA EMG detection), H values declined an additional 26%. This was significantly different from recordings obtained 0–50 ms prior to TA activation (p = .009). From 50–100 ms post-TA EMG activation, H values declined an additional, nonsignificant 5.6% (p = .995) and maintained a level that was approximately 26.4% of resting H values (quiet standing; no TA activation) during the tonic phase of ankle dorsiflexion.
Young subjects plantar flexion: 24 years of age

Voluntary plantar flexion. — During the voluntary ankle plantar flexion task a 36.9% increase in soleus muscle H-reflex responses was noted 100 ms prior to the onset of soleus EMG activity (Figure 2A). This increase was significant (p = .001) when compared to recordings obtained -200 to -101 ms prior to soleus EMG onset, or when compared to the immediately adjacent bin (-150 to -101 ms prior to soleus EMG onset). Soleus H reflexes increased an additional 24.8% (p = .003) from 51 to 100 ms post-soleus EMG onset and maintained this level for the duration of the tonic phase of ankle plantar flexion.

All subjects in this age range had a bursting of the TA muscle prior to activation of the soleus during all trials (Figure 3) except when a forward leaning starting position was requested. This TA activation was preceded by a decrease in soleus H-reflex amplitudes. In some cases, the TA continued to contract slightly during the plantar flexion task.

Subjects 56–78 Years of Age

Voluntary dorsiflexion. — Older subjects had a nonsignificant 11.6% decrease (p = .781) in H-reflex amplitudes -100 to -50 ms prior to the onset of TA muscle EMG activation and a 10.8% decrease (p = .828), 0 to -50 ms prior to TA activation (Figure 1B). Immediately following TA activation (0–50 ms post-activation), H values declined an additional 16.9%. This was a nonsignificant decrease from recordings of the previous bin (0–50 ms pre-TA contraction) (p = .381). From 50 to 100 ms post-TA EMG activation, H-reflex amplitudes decreased an additional 20.2% (p = .165) and maintained a level that was approximately 27.2% of resting H values during the tonic phase of ankle dorsiflexion. The soleus H-reflex recordings during the tonic phase of dorsiflexion were significantly different from all recordings obtained prior to TA contraction (p = .000).

All subjects [young (16–45 years) and old (56–78 years)] exhibited inhibition of the soleus motoneuron pool prior to TA activation, as evidenced by the decrease in the H reflex, 0–50 ms prior to the onset of TA activity. The degree of decrease in the younger subjects, however, was approximately twice that of the nonsignificant decreases of the older subjects (22.2% vs 10.8%, respectively). Within 50 ms of TA activation, younger subjects achieved a maximum level of soleus H-reflex inhibition that was maintained for the remainder of the tonic dorsiflexion. Older subjects required 100 ms post-TA activation to achieve maximum levels of soleus H-reflex inhibition. The relative amount of antagonist muscle alpha motoneuron inhibition during tonic ankle dorsiflexion (26.4% of resting H-reflex values for younger subjects and 27.2% of resting H-reflex values for older subjects) was similar between the two groups.
PLANTAR FLEXION  
65 YEARS OF AGE

Figure 4. Single ankle plantar flexion trial of an older subject. All labeling is similar to Figure 3. Note that there is a reversal of the activations of the TA and soleus muscles. Other atypical muscle sequencing temporal variations were seen in other trials of older subjects.

There were no observable differences in background soleus or TA EMG activity prior to or during movement between the two groups.

Voluntary plantar flexion. — During the voluntary plantar flexion task, a nonsignificant 11.6% increase in soleus muscle H-reflex responses was noted 100 ms prior to detection of soleus EMG activity \( (p = .64) \) (Figure 2B). Soleus H reflexes increased by 21.2% 0–50 ms prior to soleus muscle activation \( (p = .008) \). Immediately following soleus EMG onset (0–50 ms post-activation), soleus H reflexes increased an additional 9.1% \( (p = .815) \). From 51 to 100 ms post-soleus EMG activation, soleus H reflexes increased an additional 21.9% \( (p = .012) \) and maintained this level for the duration of the tonic phase of ankle plantar flexion.

In contrast to younger subjects, older subjects did not always contract the TA muscle prior to soleus activation during the plantar flexion task. Only 3 of 12 subjects demonstrated this typical pattern during all trials. Various atypical EMG patterns were employed by the older subjects. These patterns included initial activation of the soleus followed by TA activation (4 of 12 subjects) (Figure 4), co-contraction (>1 mV TA EMG) during the movement (6 of 12) (Figure 4), long contraction duration of the TA prior to activation of the soleus (7 of 12), and total absence of TA contraction (1 of 12). Some subjects combined more than one atypical pattern within a single trial and/or among trials. All but one subject, however, exhibited a TA burst, followed by soleus activation typical of younger subjects during at least five of the ten plantar flexion trials.

DISCUSSION

Present results are consistent with the hypothesis that the coupling between motor behaviors involved in anticipation and initiation of voluntary movements is centrally programmed and task-specific. Further, this centrally mediated coupling appears to be compromised with aging in a way that could contribute to diminished motor control characteristics of older people.

Delays in the modulation of excitability of spinal reflexes, specifically the H reflex, were apparent with the older subjects. Our data indicate that there was not a significant change in the magnitude of change of H-reflex amplitudes during voluntary ankle dorsiflexions and plantar flexions of older subjects. The time required for these modulations, however, was significantly increased. Enhancement of the soleus H-reflex 100 ms prior to onset of soleus EMG during ankle plantar flexion and the inhibition 0–50 ms prior to voluntary dorsiflexion of younger subjects are considered to be appropriate anticipatory behaviors that contribute to well-coordinated movements (22,24,25). Aged subjects consistently demonstrated delays in these responses. Another laboratory has examined H-reflex changes associated with ankle dorsiflexion using single H-reflex stimulation procedures during a reaction task (8). Similar to present findings, they also reported a delay in H-reflex modulations during the task. The delayed modulation of reflex excitability, either inhibitory or facilitatory, is a factor that can contribute to age-related impairments of motor capabilities. Delays in reflex modulation were not the only changes we observed in the older subjects.

Similar to previous studies (9,12,26,27), our results indicated that a singular consistent strategy for voluntary motor behavior was not employed by older people. We found that the temporal organization of anticipatory muscle activations that preceded voluntary movement was variable (e.g., Figure 4). Unlike younger subjects, older subjects did not use a single EMG temporal pattern during the ankle plantar flexion task.

It is very likely that delays in reflex modulation of alpha motoneuron excitability and inconsistent coupling between antagonist muscles contribute to motor coordination difficulties of older individuals. Further, we propose that these deficits are mediated, at least in part, by supraspinal mechanisms and are not the result solely of changes in excitability at the segmental level. The consistency of our results (i.e., delayed upward or downward modulation of excitability of the H reflex of older subjects) under widely ranging background conditions of speed of movement, body position, background EMG activity, and muscle length argues against segmental reflex influences having the primary role in coordinating anticipatory and voluntary movements. This is consistent with the reported lack of age-related changes in lower extremity deep tendon reflexes and responses to propriospinal input (28). Because our protocol involved voluntary, unrestrained movements at self-selected speeds, changes in corticofugal projections or their targets appear to be the most likely candidates to account for our observations. The suggestion that age-related changes in corticofugal projections result in delayed modulations of alpha motoneurons during voluntary movement is consistent with previous human and nonhuman studies.

There is a loss of corticospinal fibers in the human with advanced aging (29). Recordings from motor cortical neurons in the rabbit indicated decreased neuronal excitability with aging (30). Neurons within the primary motor cortex required increased peripheral cutaneous input in order to reach threshold. Hypothetically, activation of fewer motor cortical neurons during a volitional task could result in less
descending spatial summation at the segmental motoneuron level and, therefore, an increased afferent input requirement for modulation.

There is also a loss of alpha motoneurons with aging (31). Consequently, it might be suggested that a smaller motoneuron pool contributed to smaller H-reflex changes during the present experiments. The fact that older subjects had similar percentages of excitation and inhibition of H reflexes as did younger subjects, however, would suggest that motoneuron loss did not manifest itself during functional tasks of our older subjects.

In summary, anticipatory postural responses and voluntary movements appear to be coupled, centrally programmed, and task-specific motor behaviors. The results presented here are consistent with evidence that this coupling is susceptible to change with aging, and that at least part of this change involves altered central programming. The increased variability of coordination of motor function in older subjects warrants further study to determine if changes such as those described here may prove to be predictive of future decrement of motor function.

ACKNOWLEDGMENTS

We wish to express our appreciation to Dr. Kathleen Miller for her consultations regarding statistical analysis and Drs. Ann Williams and Thomas Sinkjaer for their reviews of the manuscript. This work was supported by grants from the National Institutes of Health (NINDS-IR15NS3066401A1), The M.J. Murdock Foundation, and The University of Montana.

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Received June 10, 1996
Accepted February 27, 1997