Timing of muscle activity during reaching while standing: systematic changes with target distance

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Abstract

We examined the effects of changing target distance from within arm’s length (AL) to beyond arm’s length on the onsets of electromyographic (EMG) activity of non-focal muscles for a reaching task performed while standing. Two questions were addressed. First, do changes in target distance result in consistent changes in the onsets of non-focal anticipatory muscle activity of the trunk and legs in healthy subjects? Second, do changes in onsets of all non-focal muscles vary in a similar fashion in response to varying target distance? Thirteen young, healthy adults performed rapid, bilateral reaching movements to targets placed at shoulder height at four distances while electromyographic activity was recorded from muscles of the arm, trunk and legs. Ground reaction forces and arm kinematics were also recorded. The onsets of most non-focal muscles occurred prior to the onset of arm movement, and occurred progressively earlier as target distance was increased. An exception to this trend was the onset of the erector spinae muscle, which occurred progressively later as target distance was increased. These data support the notion that reaches to targets beyond arm’s length involve anticipatory non-focal muscle activity that acts to transport the arm to the target rather than simply to resist the perturbation caused by the arm movement. The consistent patterns of anticipatory muscle activity observed in healthy subjects provide a template against which to compare activity patterns of non-focal muscles for individuals with potential deficits in the control of standing balance.

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1. Introduction

It is well established that muscles far removed from the focal muscle group become active during arm movements that are performed while standing [1–6]. Some of the observed electromyographic (EMG) activity is anticipatory, i.e. it occurs in advance of the focal movement or focal muscle EMG. The anticipatory activity is presumed to play a postural role in that it prevents one from falling due to the perturbation caused by the arm movement [7]. That perturbation is a combination of the net horizontal displacement of the center of mass and the motion-dependent forces generated by the multitude of linked body segments.

Non-focal muscle activity is influenced by a number of reaching task parameters, such as reaching speed [5,8], reaching direction [1,4,9], and inertial load [1,3,4]. Changes in these task parameters affect the magnitude and direction of the forces that perturb balance. As the direction and speed of reaching movements are varied, the non-focal muscle activity also changes.

With changes in reaching distance, too, the challenge to standing balance is varied. As reaching distance is increased, displacement of the whole body center of mass is increased [10,11]. In addition, when the target is placed beyond arm’s length (AL), the trunk must experience a net displacement for the hand to reach the target, whereas for shorter distances, the trunk is not obligated by configuration to move.

Kaminski and Simpkins [10] made comparisons of displacements of center of pressure and center of mass across a range of reach distances. They asked nine healthy adults to stand and perform reach-and-grasp movements to a target (dowel) that was placed in front at approximately hip height. Their results support the notion that as target distance is increased beyond arm’s length, the non-focal segments act more to move the arm to the target and not solely to resist the perturbation to standing balance generated by the arm movement. Nevertheless, the kinematics of the hand remain qualitatively similar across target distance [12–14].
Kinematics have been evaluated for reaching to various target distances while sitting [12,14] and while standing [10]. EMG patterns have been reported by Stapley et al. [11] for a whole body reaching task performed from a standing position. They asked six healthy subjects to reach, grasp, and lift an object that was placed on the floor in only two locations. We used a reaching task to multiple targets placed at shoulder height. We quantified the timing of non-focal EMG activity to characterize the manner in which the nervous system executes reaching while standing when target distance is varied in a systematic manner. By varying target distance, the challenge to standing balance is modulated by changing the magnitude of the balance perturbation and by changing the required net displacement of body segments other than the arm to successfully perform the task.

By quantifying the onsets of non-focal anticipatory muscle activity during a rapid, bilateral reaching task to varying target distances, we can address two questions. First, do changes in target distance from within arm’s length to beyond arm’s length result in consistent changes in the onset of non-focal anticipatory muscle activity of the trunk and legs in healthy subjects? If so, these patterns may serve as a template for comparison with the anticipatory muscle activity in persons with neurological conditions that may impair control of standing balance. Second, do changes in onsets of all non-focal muscles vary in a similar fashion in response to varying target distance? Similar changes in onsets of all non-focal muscles would suggest a constant postural role for those muscles across target distance. Conversely, qualitative differences in the onset patterns between non-focal muscles would suggest that such activity does not occur solely to resist a postural perturbation. We collected kinematic data of the arm and center of pressure data to provide some characterization of the modulation of the postural perturbation with target distance. A preliminary report of these results has been published in abstract form [15].

2. Methods

2.1 Subjects

Thirteen healthy subjects participated: seven female (24.3 ± 0.7 years old) and six male (24.3 ± 1.8 years old). Prior to participation in this study, all subjects provided informed, written consent in accordance with requirements of the Institutional Review Board at the University of Nebraska Medical Center.

2.2 Task

Subjects stood barefoot on a force platform with arms at the side of the body. From that position, they performed bilateral reaching movements to a visible target placed in front of them at shoulder height. They were instructed to initiate the movements in response to a computer-generated auditory “go” signal and to reach toward the target as quickly as possible. Four different target distances were used: (1) arm’s length anterior to the shoulder; (2) 10 cm less than AL; (3) 10 cm beyond AL; and (4) 20 cm beyond AL. The order of presentation of target distance was randomized, with subjects performing 10 trials of each reach distance.

2.3 Instrumentation

The target consisted of a 6 cm² piece of brass foil mounted on a flexible foam bar that was adjustable to shoulder height and appropriate target distances for each subject. Touching the metal target with a metal contact on the subject’s index finger closed a low-voltage circuit to indicate target acquisition. A tri-axial piezoelectric accelerometer (BioPac; Goleta, CA; output ±5 g, 400 mV/g) was attached to the subject’s wrist. We used the signal from the accelerometer’s axis perpendicular to the long axis of the forearm to determine the precise time of onset of arm movement. Prior to each data collection session, the accelerometer was calibrated as specified by the manufacturer.

Additional kinematic data were collected using a two-camera, three-dimensional, infrared motion analysis system (Northern Digital; Waterloo, ON, Canada). Active infrared markers were placed on the left elbow, wrist, and index finger, as well as on the target. The cameras were placed approximately 3 m away from subject, oriented approximately 60° apart. Prior to each data collection session, the equipment was calibrated as specified by the manufacturer. We accepted calibration mean marker position errors of less than 5 mm.

Bipolar, pre-amplified, surface electrodes (Therapeutics Unlimited, Iowa City, IA) were used to monitor electrical activity of seven muscles on the subject’s left side. Following skin preparation, the electrodes were placed over the anterior deltoid (AD), lumbar erector spinae (ES), vastus lateralis (VL), biceps femoris (BF), tibialis anterior (TA), lateral gastrocnemius (LG) and soleus (SO) muscles. The electrode for SO was located distal to the inferior border of LG, and approximately 10–15 cm away from the LG electrode. Signals were high-pass filtered (cutoff 20 Hz), amplified, and root-mean square (rms) processed (low-pass time constant = 2.5 ms) prior to sampling.

Center of pressure in the anterior–posterior direction (COPy) was calculated from the four vertical ground reaction force outputs (left front, right front, left rear, right rear) obtained directly from the 20-pin connector of the force platform’s electrical controller (Balance Master, NeuroCom; Clackamas, OR). The manufacturer’s Operator’s Manual provided the calibration of the ground reaction force outputs (55 mV/kg), and calculation for COPy:

\[
\text{COPy} = \frac{\left( \text{left front} + \text{right front} \right) - \left( \text{left rear} + \text{right rear} \right)}{\left( \text{left front} + \text{right front} + \text{left rear} + \text{right rear} \right)} \times 20.675 \text{ cm.}
\]
Data were collected on two computer systems. On one computer, signals from the EMG amplifiers, force platform, accelerometer, and target circuit were sampled at a rate of 1000Hz per channel by a 16 bit analog-to-digital converter and stored for later analysis. On the other computer, marker data for the kinematic analyses were sampled at a rate of 250Hz. Initiation of data collection by the two systems was synchronized using a 5 V electronic trigger signal, and the data collection window was 3 s per trial for both systems. The auditory “go” signal to the subject was generated 500 ms after initiation of data collection to allow for capture of pre-movement baseline data.

2.4. Protocol

Measurements of height, weight, arm length (tip of acromion to distal end of the index finger), and maximal reach distance were obtained (Table 1). Arm length was then used to customize the target distances for each subject. Subjects were allowed to find a comfortable stance position on the force platform, and the platform was marked in order to maintain consistent foot placement throughout the session.

At each target distance, subjects were allowed 1–3 practice reaches prior to collecting data for 10 reaches to that distance. For each trial, the subject was asked to indicate when s/he was ready to perform the task. Data collection was initiated within 1–5 s later. The subject heard the auditory go signal to start the movement. The solid vertical line indicates the time at which the subject received the auditory signal to start the movement. The solid vertical line indicates the identified onset of arm movement (time = 641 ms from the beginning of data collection).

Table 1. Subject characteristics

<table>
<thead>
<tr>
<th></th>
<th>Female (n = 7)</th>
<th>Male (n = 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, mean (±S.D.) (year)</td>
<td>24.3 ± 0.8</td>
<td>24.3 ± 1.9</td>
</tr>
<tr>
<td>Height, mean (±S.D.) (cm)</td>
<td>167.6 ± 5.8</td>
<td>181.0 ± 4.3</td>
</tr>
<tr>
<td>Weight, mean (±S.D.) (kg)</td>
<td>67.8 ± 11.0</td>
<td>84.1 ± 11.6</td>
</tr>
<tr>
<td>Arm length, mean (±S.D.) (cm)</td>
<td>72.2 ± 2.6</td>
<td>78.7 ± 2.9</td>
</tr>
<tr>
<td>Max reach*, mean (±S.D.) (cm)</td>
<td>32.4 ± 4.4</td>
<td>28.8 ± 2.8</td>
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</tbody>
</table>

*Max reach is the distance beyond arm’s length that the subject can reach and hold.

was determined by a computer algorithm that first identified peak wrist acceleration, then searched backwards to find the time at which the acceleration trace first exceeded the baseline (mean value of signal over first 250 ms of the trial). One investigator then visually confirmed the computer-identified acceleration onset and rejected the trial if there were artifacts that may have been due to backward movement of the hand or slow hand movement prior to the onset of the reach. The total number of trials rejected due to inability to identify a distinct onset of wrist acceleration was 45 out of a total of 520 movement trials (8.6%).

After movement onsets were identified, EMG and COPy data were averaged for each subject for all trials to a given target distance (maximum of 10 trials, minimum of 6 trials to each distance). Fig. 2 illustrates averaged data for 10 trials performed by one subject to a target distance of ±20 cm. EMG onsets were then identified from averaged traces using a computer-assisted operator selection process. The algorithm for identifying EMG onsets determined the point at which the rms EMG first exceeded the resting baseline by at least 2S.D. (mean of the first 250 ms of the trial) for a minimum of 5 ms. Computer-selected EMG onsets were
3. Results

3.1. EMG onsets as target distance was varied

Most of the non-focal muscles displayed consistent EMG patterns relative to the onset of arm movement that varied in a progressive fashion as target distance was varied from within arm’s length to beyond arm’s length. These patterns are apparent in the averaged traces from a single subject in Fig. 3, and in the mean EMG onsets from all subjects in Fig. 4. Analysis of variance demonstrated a significant effect of target distance on the onsets of ES, TA, VL, and SO ($P < 0.007$).

As target distance was increased, the TA and VL displayed a progressively earlier onset (see Figs. 3 and 4). For the shortest target distance, the mean onset of TA was 158 ms prior to the onset of arm movement. For all but two subjects, the TA was the muscle with the earliest onset at the longest target distance, +20. Distance-dependent changes in onsets of VL approximately paralleled those of TA.

In marked contrast to the progressively earlier onsets of TA and VL, the onset of ES became progressively later as target distance was increased. For the shortest target distance, not only was the group mean onset of ES prior to the onset of arm movement, but this onset prior to arm movement was observed in the data of all individual subjects. For the longest target distance, mean onset of ES occurred 65 ms after the onset of arm movement, and all but three subjects had offsets at +20 that were consistent with this pattern.

The only other non-focal muscle with offsets that differed significantly across target distance was SO, but mean offsets did not vary monotonically with target distance (see Fig. 4). Statistical tests did not yield significant changes in mean offsets across target distance for BF or LG.

For those non-focal muscles with significant changes in EMG offsets across target distance, post-hoc pair-wise comparisons indicated that offsets for the longest target distance, +20, were significantly different from the offsets for the shortest target distance, −10 (Table 2). In addition, offsets for +20 were different from offsets for AL for most of those muscles. EMG offsets at AL were not different from those at +10 for any of the muscles, and only different from those at −10 for the VL.

Table 2

<table>
<thead>
<tr>
<th>AL vs.</th>
<th>ES</th>
<th>VL</th>
<th>TA</th>
<th>SO</th>
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<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>+20</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.011</td>
</tr>
<tr>
<td>10</td>
<td></td>
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<tr>
<td>+10</td>
<td>&lt;0.001</td>
<td>0.015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>−10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AL</td>
<td></td>
<td></td>
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<tr>
<td>+20</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
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<tr>
<td>AL</td>
<td></td>
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<td>+10</td>
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<tr>
<td>+10</td>
<td>0.027</td>
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All statistical analyses were performed using SigmaStat version 2.03 (SPSS).
Fig. 3. Examples of averaged EMG and COPy for all target distances. Data are from subject T. Each trace represents the average of 9–10 trials. Averaged traces of AD, ES, VL, TA, and COPy are shown. Calibration bars to the right represent: 6μV (AD), 2μV (ES), 2μV (VL), 1μV (TA), 30μV (SO). In each group of traces, the shortest target distance (−10) is at the top and the longest target distance (+20) is at the bottom. All traces are aligned relative to the onset of arm movement (time = 0 ms).

3.2. Biomechanical measures as target distance was varied

The overall temporal pattern of COPy illustrated in Figs. 1 and 2 was typical for all target distances (Fig. 3). As illustrated in these figures, the point of application of the ground reaction force moved backward then forward in association with the arm moving in a forward direction.

We analyzed the peak-to-peak and net displacement of COPy as indications of the magnitudes of the perturbation to standing balance. Both the net displacement and the peak-to-peak displacement increased \((P < 0.001)\) as target distance increased (Fig. 5). Post-hoc comparisons confirmed that values of both COPnet and COPp-p were significantly different at each target distance. Changing the target distance from within arm’s length to beyond arm’s length was associated with consistent, progressively increasing balance perturbations. Yet, while the magnitude of changes in COPy increased with distance, the qualitative pattern remained the same.

In addition to COPy displacement, we evaluated peak tangential velocity of the fingertip and time to peak velocity.

Fig. 4. Mean onsets of EMG for all target distances \((n = 13)\). The shortest distance (−10) is at the top, and the longest target distance (+20) is at the bottom. EMG onsets are relative to the onset of arm movement. Negative values indicate onset before the onset of arm movement. Muscles represented are anterior deltoid (AD), erector spinae (ES), vastus lateralis (VL), tibialis anterior (TA), and soleus (SO).

Fig. 5. Mean (+S.D.) displacements of center of pressure (COPy) for all target distances \((n = 13)\). Unfilled bars represent net displacement (post-movement COPy − pre-movement COPy). Filled bars represent peak-to-peak displacement (during movement).
traces might suggest (see Fig. 3). The other ankle plantar
stance (Fig. 4, Table 2). Onsets of muscles with variable
tent patterns of change in response to varying target dis-
ance, the identification of the onsets of some mus-
ons was certainly easier than that of others. The onsets
ble onsets, the identification of the onsets of some mus-
movement provided us with reliably identifiable
patterns.

4. Discussion

In this study, we used a reaching paradigm to evaluate
the influence of target distance on onsets of EMG activity
in non-focal muscles. We aligned temporal events relative
to the onsets of arm movement and then averaged data over
several trials. This process provided consistent, identifiable
onsets of EMG activity. These systematic modulations were
observable in single trials (Fig. 1), in averages over multiple
trials (Figs. 2 and 3), and in the mean onsets from all subjects
(Fig. 4). The statistical analyses supported these observed
patterns.

4.1. The influence of target distance

The first aim of this study was to characterize the
effect of target distance on onsets of EMG activity in
non-focal muscles of healthy adults. In agreement with
previous studies, focal muscle activity of AD and subse-
quently arm movement were preceded by non-focal muscle
activity [2,3,5,6,14]. All target distances were associ-
ated with anticipatory non-focal muscle activity, which
for the longer target distances appeared remarkably early.
The anticipatory nature of the non-focal muscle activ-
ity indicates that it is preplanned by the nervous system
in conjunction with the focal muscle activity and focal
movement.

Although our process of averaging trials relative to the
onset of arm movement provided us with reliably identifi-
able onsets, the identification of the onsets of some mus-
cles was certainly easier than that of others. The onsets
of TA, VL, and ES showed the clearest and most consis-
tent patterns of change in response to varying target dis-
nance (Fig. 4, Table 2). Onsets of muscles with variable
baseline activity were sometimes difficult to determine (BF,
LG). Onsets were also more difficult to identify for short
target distances where changes in EMG were sometimes
small (e.g. TA). Because our algorithm for identifying on-
sets used the mean and standard deviation of that base-
line period, onsets of muscles such as SO seemed more
variable (see Fig. 4) than a visual gestalt of the averaged
traces might suggest (see Fig. 3). The other ankle plantar
flexor that we recorded, LG, appeared from the EMG traces
to parallel SO, but the statistical tests did not support this
observation.

We believe that identifying consistent, distance-dependent
changes in anticipatory activity of muscles of the leg, thigh,
and trunk in healthy adults may allow detection of subtle pos-
tural control changes in individuals with balance deficits. If
so, this reaching paradigm could be useful in early detection
of balance problems that may not be apparent with the use
of standard clinical balance tests such as the Berg Balance
Scale [16] or Functional Reach test [17]. This task could
also be useful in assessing the efficacy of various physical
or pharmacological interventions aimed at reducing balance
deficits.

In addition to EMG onsets, measures of COPy also varied
with target distance. As target distance was increased, net
displacement of COPy increased, indicating that the whole
body center of mass moved a greater distance, generating a
larger static perturbation to standing balance. In addition, the
peak-to-peak COPy also increased with distance, suggesting
a larger dynamic component to the postural perturbation and
adjustment. Qualitatively, however, the trajectories of COPy
changed minimally. For all target distances, COPy initially
moved posteriorly, then anteriorly, then to a steady final
position. These data confirm that the task parameter of target
distance had an effect on the magnitude, but not the direction
of the postural perturbation. The patterns that we observed
are consistent with data of COP trajectories presented by
Hodges et al. [4] and Kaminski and Simpkins [10], in which
COP first moved in a posterior direction, then anteriorly.

The hand velocity data gathered may be more revealing
than statistical results indicated. Typically when subjects are
asked to reach as fast as possible using only the arm (with
no trunk or body movement), peak hand velocity increases
as reach distance increases [18]. In contrast, our data would
suggest that as the target is placed at greater distances (20 cm
beyond arm’s length), the reaches become slower, perhaps
to minimize the destabilizing effect of motion-dependent
forces related to the arm movement.

4.2. The nature of “non-focal” EMG activity

The second question we addressed was whether onsets
of all non-focal muscles varied in a qualitatively similar
fashion, which would suggest a constant postural role for
these muscles across target distance. Onsets of several of the
non-focal muscles varied systematically with target distance,
yet they did not all vary in the same fashion. The TA and VL
onsets became increasingly early as target distance was in-
creased, while the ES onsets became increasingly late. Con-
sidering previous studies of similar movement tasks, these
results support the notion that for the initiation of reaching
movements, non-focal muscles change from playing a pos-
tural role for short reaches to playing a transport role for
long reaches.

In previous studies of shoulder flexion movements per-
formed while standing, the non-focal muscle activity has
been considered to act in opposition to the destabilizing effects of the focal arm movement on standing balance, and has therefore been referred to as an anticipatory, or associated, postural adjustment [1–3, 5, 6, 8, 19]. These studies contain examples of tri-phasic EMG patterns in which posterior non-focal muscles (e.g. trunk extensors, hamstring muscles) become active in advance of anterior non-focal muscles. This pattern makes sense if the muscles are acting to resist the perturbation due to the arm movement. In our study, reaches to –10 and to AL were associated with non-focal EMG onsets that were consistent with these previous results. However, this pattern was not observed when subjects performed reaches to targets beyond arm’s length, where TA and VL consistently showed the earliest onsets for the longer reaches, while ES onsets were not observed until after movement initiation. If onsets of non-focal muscles were acting to resist postural perturbations for target distances beyond arm’s length, the relative timing of those onsets would have remained qualitatively similar across target distance. This did not occur, suggesting that non-focal muscle activity for reaching movements beyond arm’s length does not act to resist a postural perturbation.

Instead, our data indicate the changing role of the non-focal muscle activity as target distance increases. For target distances beyond arm’s length, the anterior muscles (TA, VL) become active well in advance of the arm movement, not to resist the impending perturbation to balance, but to launch the body and arm forward. The ES muscle becomes active well after movement initiation, likely acting to slow the trunk’s motion. Work by Kaminski and Simpkins [10] is consistent with our interpretation of changes in EMG onsets. The changes they observed in the center of mass and center of pressure also suggest that target distance may dictate whether anticipatory adjustments fulfill a postural role.

Wang and Stelmach [14] studied reach-and-grasp movements performed while seated, that required trunk involvement. The object targeted for grasp was a sufficient distance from the initial hand position, thus necessitating trunk forward flexion to reach the object. They provided kinematic evidence that the trunk and arm may be controlled independently, but are coordinated by a higher level controller. They suggested the involvement of a control hierarchy that “functionally united” the arm and trunk to transport the hand. In effect, for reaches beyond arm’s length, the trunk became a segment of the arm. The activity we observed in ES is consistent with this notion.

In conclusion, target distance had a powerful effect on onsets of EMG activity for many non-focal muscles used for reaching while standing. These results suggest that non-focal muscles initiate reaching movements to targets beyond arm’s length by assisting the reach instead of resisting the perturbation caused by the reach. Because the successful coordination of voluntary arm movements and standing balance is a common daily necessity, it is worth characterizing the effect of the task parameter of target distance on muscle activity patterns in normal, healthy adults. These results can thus provide a template against which to compare parameters in individuals with postural control deficits.

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References


