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Electromechanical response times and muscle elasticity in men and women

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Summary. The purpose of this study was to compare the delay in performance attributable to muscle elasticity in men and women. A group of 11 active young men age (mean, SE) 21.9, 0.7 years, stature 1.780, 0.020 m, body mass 76.4, 3.2 kg and 11 women age 20.9, 0.4 years, stature 1.670, 0.020 m and body mass 61.9, 2.6 kg provided written informed consent and were recruited to the study. In response to an acoustic signal delivered via headphones, the subjects performed a plantar flexion movement of the preferred leg as quickly as possible. A seated position ensured that the knee of the subject was flexed at a right angle and that the shank was vertical. The ball of the foot was on a force platform which was used detect the onset of muscle tension and the heel rested on a pressure pad which was used to identify movement. Surface electrodes sensed electromyographic activity (EMG) in the soleus muscle. Force platform output was captured by a digital storage oscilloscope and recorded via a y-t pen recorder for subsequent analysis. A separate timer was used to determine total reaction time (TRT). Premotor time (EMGT) was taken to be the time interval from the delivery of the signal to change in EMG. Electromechanical delay (EMD) was the time interval between the change in EMG and movement and was subdivided into force time (FT) i.e. the time interval between EMG and the onset of muscle tension and elastic charge time (CT) i.e. the time interval between the onset of muscle tension and movement. The subjects performed ten trials and in most cases the mean of ten readings was used to determine TRT, EMGT, EMD, FT and CT. There were no differences between men and women in TRT (163.3, 5.6 ms vs 176.2, 6.3 ms; $P=0.149$), EMGT (123.6, 6.0 ms vs 131.8, 6.4 ms; $P=0.359$) and FT (9.5, 1.1 ms vs 10.9, 1.2 ms; $P=0.400$) whereas there were differences in EMD (39.6, 1.2 ms vs 44.9, 2.0 ms; $P=0.037$) and CT (30.2, 1.3 ms vs 34.1, 1.3 ms; $P=0.044$). The results suggest that there are sex-linked differences in musculotendinous elasticity and these might in part account for observed performance differences.

Key words: Muscle elasticity – Electromechanical response times

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Introduction

The delay between the onset of electrical activity and force generation in muscle has previously been investigated via two distinct time periods (Weiss 1965; Viitasalo et al. 1980; Bell and Jacobs 1986). First, there is the interval between the receipt of the signal at the motor end plate and a change of electrical activity across the sarcolemma and second, the electromechanical delay (EMD), which is the time interval between the change in electrical activity and movement. It has been suggested that EMD is associated predominantly with the time it takes to lengthen the elastic elements (Alexander and Bennet-Clark 1977; Viitasalo and Komi 1981). Collectively these time intervals are referred to as "electromechanical response times".

Comparisons between EMD in men and women have demonstrated differences (Bell and Jacobs 1986). These could be attributable to differences in neuromotor control which involves the conduction of the action potential along the T tubule system, the release of Ca^{2+} by the sarcoplasmic reticulum, cross bridge formation between actin and myosin filaments, the subsequent tension development in the shortening elements (Cavanagh and Komi 1979; Karlsson et al. 1981; Muro and Nagata 1985) and the series elastic component which in men is more resistant to stretch (Komi 1984).

In a number of studies on humans (Cavanagh and Komi 1979; Morris and Beaudet 1980; Bell and Jacobs 1986) and rats (Kamen et al. 1988) isometric muscle activity has been the exercise model whereas in others, the end point has been movement (McIlwain and Hayes 1977; Norman and Komi 1979; Viitasalo and Komi 1981). The distinction is important if muscle elasticity is under consideration. A simple tow rope illustrates the point. If a car is to be towed, initially the slack in the rope is taken up and then it can be seen quite clearly as the rope stretches that tension develops before movement of the towed car occurs. A measure of the elasticity of the system is the extension observed in the rope. This in turn influences the period of the delay between the development of tension and actual movement. A similar process occurs in muscle, so that if elasticity is under scrutiny then it is the onset of movement which must identify the limit of consideration.

By allowing movement to occur the purpose of this study was to compare the delay in performance attributable to muscle elasticity in men and women.

Methods

The subjects recruited to the study were 11 men and 11 women undergraduate Physical Education or Sports Studies students who were fully accustomed to the procedures and who provided written informed consent. All subjects were highly active and usually took part in vigorous exercise on a daily basis. Their details are displayed in Table 1.

Electromechanical response times were determined using a technique presented earlier (Winter and Brookes 1990) but described in detail here. The subject sat on a wooden chair (to prevent the generation and accumulation of static electric charge) with the knee of the preferred leg flexed at approximately 1.57 rad. The ball of the foot was positioned on a force platform (Kistler 9281 A) and the heel rested on a pressure pad (RS Components). With appropriate areas shaved and rubbed vigorously with alcohol to minimise inter-electrode resistance, surface electrodes 10-mm diameter were placed 3–4 cm apart over the lateral surface of the soleus muscle which had been identified by inspection and palpation. The soleus muscle was chosen because it is a single-joint muscle and differences attributable to joint laxity were minimised. Furthermore, with the knee flexed there is little or no contribution from the gastrocnemius muscle during plantar flexion. A reference electrode was positioned over the lateral epicondyle of the femur.

After a visual warning, a randomly ascribed auditory signal was delivered to the subject through headphones within 1–4 s. Upon receipt of the signal the subject plantar flexed the foot as quickly as possible. Care was taken to ensure that the subject was not exposed to any distractions which might have affected their performance. In addition to the subject only two investigators were present during data capture.

An electromyogram (EMG) was detected by the electrodes and amplified by a wide band, differential input, AC coupled amplifier. The output from the force platform was amplified by a charge amplifier (Kistler 5007). EMG and the output from the charge amplifier were sampled at 2.5 kHz and recorded on a digital storage oscilloscope (Gould OS 4100). A suitable delay (40–100 ms) was introduced for each subject to ensure that recordings were displayed on the oscilloscope.

A hard copy of the data captured and stored by the oscilloscope was obtained via a y-t pen recorder (J-J Lloyd CR552) for subsequent analysis. A separate timer (Electronic Developments ED1) was used to record the time interval from the presentation of the auditory signal to movement of the heel away from the pressure pad. A process timer (Electronic Developments E10) controlled the administration of the stimulus and synchronised the timing equipment. An example of the output is displayed in Fig. 1.

Five characteristics were determined:

(1) Total reaction time (TRT), defined as the time interval from the application of the auditory stimulus to movement of the heel away from the pressure pad.

Table 1. Details of subjects [means (SE)]

	Men ($n=11$)	Women ($n=11$)	
Age (years)	21.9 (2.4)	20.9 (1.4)	$P=0.243$
Stature (m)	1.780 (6.6)	1.670 (6.9)	$P=0.001$
Body mass (kg)	76.4 (10.6)	61.9 (8.6)	$P=0.002$

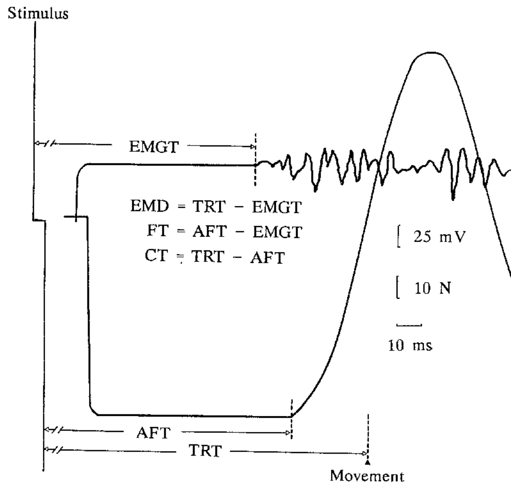

Fig. 1. An example of an EMG recording (*upper*) and force trace (*lower*) to illustrate how the time intervals were determined. *TRT*, total reaction time; *EMGT*, pre-motor time; *AFT*, time to the appearance of force; *EMD*, electromechanical delay; *FT*, force time; *CT*, elastic charge time

Table 2. Test-retest coefficients of variation (V%) of the measures compared with those of Viitasalo et al. (1980)

Measure	Men ($n=8$)	Women ($n=8$)	Viitasalo et al. (1980) (men $n=29$)
Total reaction time	6.3	6.8	16.5
Premotor time	7.1	8.3	18.8
Electromechanical delay	11.5	8.6	8.2
Force time	41.4	30.7	—
Elastic charge time	15.7	13.3	—

(2) Pre-motor time (EMGT), defined as the time interval from the application of the stimulus to the change in electrical activity of the soleus muscle.

(3) Electromechanical delay (EMD), defined as the time interval from the change in electrical activity in the soleus muscle to movement of the heel away from the pressure pad.

(4) Force time (FT), defined as the time interval from the change in electrical activity to the registration of force.

(5) Elastic charge time (CT), defined as the time interval between the registration of force and movement of the heel away from the pressure pad.

Subjects performed ten trials and in most cases the mean of ten readings was used to determine TRT, EMGT, EMD, FT and CT.

The reproducibility of the measures was assessed in a separate study in which 16 subjects (8 men and 8 women) were measured 168 h apart in an attempt to reduce the effects of circadian or other similarly induced variations in performance (Reilly 1987).

Table 3. Time intervals of the measures in men ($n=11$) and women ($n=11$). Values are in ms and are means (SE)

Measure	Men	Women	
Total reaction time	163.5 (5.6)	176.2 (6.3)	$P=0.149$
Premotor time	123.6 (6.0)	131.8 (6.4)	$P=0.359$
Electromechanical delay	39.6 (1.2)	44.9 (2.0)	$P=0.034$
Force time	9.5 (1.1)	10.9 (1.2)	$P=0.400$
Elastic charge time	30.2 (1.3)	34.1 (1.3)	$P=0.044$

Test-retest coefficients of variation (Sale and Norman 1982) were calculated and these are illustrated in Table 2 accompanied by similar data from Viitasalo et al. (1980).

Each of the measures was compared in men and women using as appropriate pooled or separate variance models of Student's *t*-test for independent data.

Results

The results are illustrated in Table 3. In Table 4, TRT and EMD are compared with data from other studies.

Time intervals for EMD and CT were shorter in the men than in the women ($P=0.037$ and 0.044 respectively) whereas for TRT, EMGT and FT no significant differences were observed ($P=0.149$, 0.359 and 0.400 respectively). Values of TRT, EMGT and EMD for both men and women were similar to those reported for men by Viitasalo et al. (1980) who recorded 162.3, 5.6 ms, 124.3, 6.2 ms and 38.0, 1.7 ms (mean, SE) respectively. The values of FT in this study are comparable with data reported by Muro and Nagata (1985), whose protocol distinguished between the appearance of force and actual movement, although the latter was not assessed, which were 11.7 ± 1.6 ms in unstretched soleus muscle of men and 7.0 ± 1.2 ms in heavily stretched muscle. Again the similarities are striking although it should be noted that the reproducibility of FT in both men and women is not as strong as that of the other variables. This might be attributable to the resolution with which the measures could be read i.e. 1 ms. This represents approximately 10% of FT so it is not surprising that the test-retest coefficients of variation were higher than for other indices.

Discussion

Comparisons between the results of different studies have to made cautiously and are often confusing. There are a number of reasons why this should be the case. First the stimulus which is used to initiate responses will in itself influence TRT. An acoustic signal produces a shorter total reaction time than a light stimulus and this is illustrated clearly in Table 4. This observation is attributable to differences in the time it takes for the visual sense organs to detect changes in light intensity and the auditory senses to respond to sound. The

Table 4. A comparison of published values for total reaction time (TRT) and electromechanical delay (EMD)

Study	*n*	Sex	Joint	Movement	Stimulus	Interval (ms)	
						TRT	EMD
Weiss (1965)	14	M	Finger	Concentric Extension	Sound	173.9	64.6
Schmidt and Stull (1970)	30	M	Finger	Isometric Flexion	Sound	140.3	34.5
Viitasalo and Komi (1981)	29	M	Knee	Isometric Extension	Sound	161.4	38.3[a]
Present study	11	M	Ankle	Plantar Flexion	Sound	163.5	39.6[b]
	11	F	Ankle	Plantar Flexion	Sound	176.2	44.9[b]
Schmidt and Stull (1970)	30	M	Finger	Isometric Flexion	Light	231.8	39.2
Kroll (1974)	11	M and F	Knee	Concentric Extension	Light	246.0	
Cavanagh and Komi (1979)	14	M	Elbow Elbow Elbow	Eccentric Isometric Concentric	Light Light Light		49.5[c] 53.9[c] 55.5[c]
Bell and Jacobs (1986)	86	M and F	Elbow	Isometric Flexion	Light	194.3	29.3[d]
Nilsson et al. (1977)	12	M	Knee	Isokinetic Extension	Voluntary		95.3[e]
McIlwain and Hayes (1977)	7	M	Ankle	Plantar Flexion	Reflex H Reflex M		32.0[f] 25.4[f]

[a] Strain gauge and goniometer
[b] Pressure pad
[c] Strain gauge
[d] Transducer
[e] Isokinetic
[f] Goniometer

time intervals involved are 30–40 ms and 8–10 ms respectively (Brebner and Welford 1980).

In addition, different methods have been used and this creates considerable difficulty when attempts are made to compare data. This again is illustrated in Table 4. Six techniques have been used supposedly to detect the end of EMD whereas the identification of the start of EMD was uniform i.e. a change in EMG. This study defined the end point as movement, as did McIlwain and Hayes (1977), Norman and Komi (1979) and Viitasalo and Komi (1981). This contrasts with studies which have used the appearance of force as the end point (Cavanagh and Komi 1979; Morris and Beaudet 1980; Bell and Jacobs 1986). Another factor which has to be considered concerns the different muscles that have been investigated. These contain different fibre types which will influence shortening characteristics such as the time intervals involved (Viitasalo and Komi 1981; Lamb 1984).

What is clear, however, is that the onset of tension and movement are not coincident. There is a time lag between the two. Consequently, it is difficult to understand how EMD has been assessed in studies which have used isometric muscle activity as the exercise model. FT is only part of EMD and presumably, indicates conduction of the action potential along the T tubule system and subsequent release of Ca^{2+} by the sarcoplasmic reticulum. It can only be assessed if movement occurs. It is short and occupies something in the order of only 10 ms as this study and that of Muro and Nagata (1985) clearly demonstrate.

It appears that prior to this point, there are no clear sex linked differences in any of the electromechanical response times. EMD, however, is shorter in men than in women (39.6, 1.2 ms vs 44.9, 2.0 ms respectively; $P=0.034$). There is an observed difference in FT (9.5, 1.1 ms in men vs 10.9, 1.2 ms in women) but the difference is not significant statistically ($P=0.400$). This suggests that neuromuscular transmission characteristics across the sarcolemma are at least similar. However, there is a significant difference in CT, 30.2, 1.3 ms in men vs 34.1, 1.3 ms in women ($P=0.044$).

This observation could be attributable to a number of mechanisms. It could represent differences in fibre-type distribution (Viitasalo and Komi 1981; Woledge et al. 1985), type II fibres having shorter force-developing times than type I fibres. This possibility is unlikely because it has been demonstrated that systematic differences in fibre type attributable to sex do not occur (Nygaard 1981). Furthermore, the subjects were active multiple-sprint-type sportspeople who participated at a high level in activities such as hockey, association football, netball and basketball. The observed differences could have been attributable to greater joint laxity in women (Lamb 1984; Fox et al. 1988), but while this mechanism cannot be discounted, the selection of the soleus muscle, a single-joint muscle, was made carefully in an attempt to reduce the possible contribution from this source.

Biochemical characteristics of skeletal muscle which influence the rate of cross-bridge coupling could have

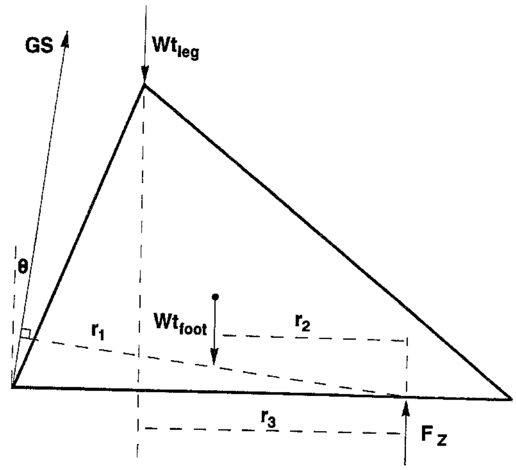

Fig. 2. A simplified diagram of the forces acting on the foot leading to plantar flexion. *GS* is the force developed in the gastrocnemius and soleus muscles to bring about plantar flexion; Wt_{foot} is the weight of the foot and Wt_{leg} the weight of the leg; r_1, r_2 and r_3 are their respective lever arms from the ball of the foot. The condition for plantar flexion to occur is: $GS \cdot r_1 > Wt_{foot} \cdot r_2 + Wt_{leg} \cdot r_3$

accounted for differences in EMD and CT. It has been demonstrated that levels of phosphofructokinase activity in the vastus lateralis muscle are lower in 16- and 25-year-old women than in age-matched men (Hedberg and Jansson 1976; Nygaard 1981). Similarly it has been demonstrated in rats that testosterone increases phosphorylase activity (Krotkiewski et al. 1980) and Bass et al. (1975) reported that the activity of other anaerobic enzymes including lactate dehydrogenase were significantly lower in women than in men. Komi and Karlsson (1979) added further support to this finding by reporting higher levels in men of Ca^{2+} adenosine triphosphatase, creatine phosphokinase and phosphorylase. Muscle biopsy samples were not taken in this study so the precise influence of these possible factors could not be assessed. The activity and training status of the two groups was similar. Both comprised highly competitive elite standard individuals, so that differences attributable to socio-cultural influences (Wells and Plowman 1983; Drinkwater 1984) were minimised.

Differences in EMD and CT could have been attributable to differences in the size and composition of the limb segments. Figure 2 illustrates the major forces that are involved during plantar flexion. However, structural characteristics such as these are difficult to account for with sufficient accuracy and have not been offered as possible explanations in the previous studies detailed in Table 4. Whilst such a possibility cannot be discounted, this study is, nevertheless, consistent with previous work in the area.

Similarly, hormonal effects could have been implicated, especially in the women (Puhl and Harmon-Brown 1986; Highet 1989). In an attempt to minimise these possible influences the recruitment procedures ensured that subjects took part in the study only after they had provided informed consent and were satisfied that their performance would not knowingly be affected by other factors.

Another possible explanation could be the elasticity of the musculotendinous unit. This study did not distinguish between muscle elasticity and tendon elasticity (Alexander and Bennet-Clark 1977) but neither have other studies which have investigated EMD (Cavanagh and Komi 1979; Viitasalo et al. 1980; Komi 1984; Bell and Jacobs 1986). This is understandable because making this distinction in vivo creates considerable difficulty. Clearly, however, elasticity of the overall musculotendinous unit has been examined. Alexander and Bennet-Clark (1977) indicated that both structures are elastic but whereas during submaximal exercise muscle elasticity predominates, when the force exerted by a muscle becomes maximal, the muscle stiffens and the elasticity of the accompanying tendon (or tendons) is harnessed. This suggests that muscle elasticity predominated in this study and that there were differences in this characteristic between men and women.

The precise mechanisms still remain elusive because the elasticity could reside, for example, in series and parallel components in muscle (and tendon), in cross-bridge attachments themselves, or elsewhere. What is clear, however, is the usefulness of this particular experimental protocol: it enables determination of the time lag between muscle stimulation and performance with a sensitivity that has previously not been obtainable. The identification of a sex-linked difference in this characteristic could explain performance differences, at least in part.

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