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Is there sufficient evidence to explain the cause of sexually dimorphic behaviour in force steadiness?

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Complete List of Authors:	Jakobi, Jennifer; University of British Columbia Okanagan Faculty of Health and Social Development Haynes, Elijah; University of British Columbia Okanagan Faculty of Health and Social Development Smart, Rowan; University of British Columbia Okanagan Faculty of Health and Social Development
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4
5 Authors: Jennifer M Jakobi, Elijah MK Haynes, Rowan R Smart

6
7 School of Health and Exercise Sciences, Healthy Exercise and Aging Lab Group, University of
8 British Columbia Okanagan, Kelowna, BC, V1V 1V7

9
10
11
12 Corresponding author:

13
14 Jennifer M. Jakobi MSc, PhD
15 jennifer.jakobi@ubc.ca
16 250-807-9884
17 Health and Exercise Sciences, Art 339
18 339-1147 Research Road (Arts Building)
19 University of British Columbia Okanagan
20 Kelowna, BC Canada V1V 1V7
21
22

Abstract

Neuromuscular noise is a determining factor in the control of isometric force steadiness (FS); quantified as coefficient of variation (CV) of force around a pre-established target output. In this paper we examine sex-related differences of neural, muscular and tendon influences on neuromuscular noise, to understand FS in females and males. We use evidence from the literature to identify that CV of force is higher in females compared with males in the upper and lower body, with sex-related differences becoming less apparent with increasing age. Evaluation of sex-related physiology in tandem with results from FS studies indicate that differences in fibre type, contractile properties and number of motor units (MUs) are unlikely contributors to differences in FS between females and males. MU type, behaviour of the population (inclusive of number of active MUs from the population), agonist-antagonist activity, maximal strength, and tendon mechanics are probable contributors to sexually dimorphic behaviour in FS. To clearly determine underlying causes of sex-related differences in FS, further study and reporting between females and males is required. Females and males are included in many studies; however, rich data on sexually dimorphic behaviour is lost when data are collapsed across sex or identified as non-significant without supporting values. This poses a challenge to identifying the underlying cause of females having higher CV of force than males. This review provides evidence of sexually dimorphic behaviour in FS and suggests that physiological differences between females and males effect neuromuscular noise, and in-turn contribute to sex-related differences in FS.

Keywords: neuromuscular noise, females, women, motor unit, common synaptic input

46

47 **Introduction**

48 Neuromuscular noise is a product of multiple subsystems (neural, muscular, tendon) that
49 ultimately through spinal synaptic activity integrate, on different time scales, to affect motor
50 output from the skeletal muscle. Neuromuscular noise is an inherent and inescapable element
51 that has been implicated in controlling human movement and is associated with the sensorimotor
52 system's ability to regulate complex interactions between the afferent and efferent input-output
53 relations. Increases in neuromuscular noise are attributed to decreases in size and number of
54 motor units (MU), orderly recruitment and discharge rate variability of MUs, as well as
55 degrading sensory information accuracy through deterioration of muscle spindle and
56 proprioceptive function (Hamilton et al. 2004, Roos and Dingwell 2010) where independent
57 elements are filtered by the pool of motoneurons and common elements compose the effective
58 neural drive (Farina and Negro 2015). The contribution of neuromuscular noise to functional
59 movement in humans is difficult to investigate, and thus isometric contraction models of force
60 steadiness (FS) are studied to define the underlying principles of neuromuscular noise that apply
61 to functional movement in sport, work and daily life.

62 During isometric contractions, force output fluctuates around an average value, and FS is
63 defined as the magnitude of variability in the force oscillations around a pre-established target
64 force. In absolute terms, FS is quantified as the standard deviation (SD) of force output around
65 the target and, in relative terms as the coefficient of variation (CV) of force (ratio of standard
66 deviation in force fluctuations relative to the mean force). It is well established that with
67 increases in isometric force the absolute size (SD) of force fluctuations increase in a linear
68 fashion (Tracy and Enoka 2002). For relative force variability, there is a non-monotonic decrease

from low to moderate forces, and as force increases beyond moderate levels CV of force also increases slightly above that of moderate forces (Figure 1A). Since CV is a dimensionless measure, the quantifiable outcome is not based on a percentage of maximal or an absolute force calculation, thus tolerating a more global appraisal across studies. We have applied CV of force as the operationalized measure to understand isometric force steadiness in females and males.

The relative force–CV of force relationship largely, but not exclusively (Graves et al. 2000), resembles that of a backwards “J” because the severity of the curve at high forces does not equate to that seen at low forces. However, caution in interpretation should be applied as most studies use single joint contractions and simplified muscle models of low forces with few studies considering moderate to high forces (Brown et al. 2010, Svendsen and Madeleine 2010, Yoon et al. 2014, Smart et al. 2018). In this paper, where FS is operationalized through the measurement of CV of force, isometric tasks are generally focalized to a single limb in an isolated joint position and non-fatigued state. In these conditions of isometric models there is evidence that across all force levels there is a discernible and well-documented higher CV of force in females than males (Figure 1A) that occurs across submaximal forces (Figure 1B) and most muscle groups (Figure 1C) measured in numerous commercial and custom-made devices, experimental scenarios, and ages.

[Insert Figure 1 Approximately Here]

Evidence of sex-related differences in these isolated models of FS allows for estimation of sources of neuromuscular noise through the study of force variability. Nonetheless, it must be acknowledged that these isometric models limit understanding of task specificity and accuracy,

as well as alterations to known elements of human conditioning such as fatigue and training. Isometric models minimize the influence of appendicular, synergistic and antagonistic muscles that are fundamental to the control of dynamic movements that encompass typical daily and occupational patterns. These elements of adaptations in whole body motor performance to acute and chronic involvements require further and independent consideration (Côté 2012) in sex-related differences in movement control.

Within this paper, sex as a biological factor will be discussed relative to FS. We inferred from the experimental design and results of studies the biological attributes associated with morphological and physiological features of females and males. No cited study identified the sample population or outcome measures that describe socially constructed roles, expression and/or identity classified as gender - woman or man. This distinction between sex and gender will likely need to evolve with the FS literature as elements of physical activity, sport, and musical training influence FS (Enoka et al. 2003) and are delineated through gender rather than sex.

Force steadiness studies centering on age, muscle group, intensity and type of contraction, as well as those inferred to gendered conditions (e.g., physical activity, training) are extensive (Enoka et al. 2003, Oomen and van Dieën 2017). The study of sex-related differences in FS is relatively diminutive, though shrewd evaluation of the literature revealed a number of investigations undertaken in females and males. However, data is lost to reporting, as many studies do not report female and male data or statistically collapse across sexes. This was historically explicable given many scientists and laboratory personnel were males and immediately accessible for recruitment. Moreover, when one considers how adding an experimental group alters statistical power, and that menstrual cycle hormones potentially

influence one experimental group (Tenan et al. 2013), the perceived barrier to the study of females was perhaps defensible. This conventional rationale is no longer acceptable in the study of human physiology as it has become well-known that every human cell is sexed and that this sexual dimorphism impacts function (Miller 2012). From this perspective, there is likely compensatory adaptations between and within human systems to account for sex-related changes in one physiological system or anatomical element, and its accommodations between and within systems that likely alter neuromuscular noise and effective neural output to influence FS differently between females and males.

Females and males differ in FS; females are less steady than males measured as a higher CV of force (Figure 1). The exact mechanism(s) of this sex-related difference in FS remain(s) unknown. It is surprising that a greater appreciative value is not placed on sex-related differences in FS between females and males because it is a simple model to understand complex functional movement of work and daily life which has demonstrable ecological relevance to functional movement (Ranganathan et al. 2001, Seynnes et al. 2005, Almuklass et al. 2016). To offer insight into potential sites of sex-related sources of neuromuscular noise contributing to differential force output between females and males, sex-related physiology literature will be applied in tandem with the knowledge from general FS studies to provide a framework of the morphological and physiological factors that can likely be disregarded and those that should be considered in the investigation of neuromuscular noise contributing to sex-related differences in FS.

Likely Factors to Discount

Many of the differences in function, sport performance and fatigability between females and males can largely be explained by muscle size and fiber type composition that ultimately influences whole-body substrate utilization (Hunter 2016). To-date, most studies have not considered these factors as possible influences in the evaluation of FS between females and males. It is imperative to identify whether individual properties of MU, fibres or whole muscle contractile properties should be included (or excluded) in studies of FS in females and males.

Fiber types and contractile properties: Summarized in prior sex-related reviews for fatigability (see Fig 4, Hunter 2016), females have a greater proportional area of type I muscle fibers compared to males. This largely arises from measures of absolute type II fiber area being smaller in females (Simoneau et al. 1985, Carter et al. 2001), while the absolute area of type I fibers does not differ between females and males (Simoneau et al. 1985). In line with the absolute area occupied by type I muscle fibers, the cross-sectional area (CSA) of individual type I muscle fibers is similar between the sexes, yet type II fibers are smaller in females (Carter et al. 2001). Thus, young females have a greater proportion of type I fibers per total fiber area, and this likely contributes to contractile properties being slower in females compared to males (Simpson et al. 2018).

The human literature reporting whole muscle contractile properties in females and males aligns with the fibre type data. The elbow flexors (Hicks and McCartney 1996), plantar flexors (Simpson et al. 2018), knee extensors (Berger et al. 2012) and dorsiflexors (Hicks and McCartney 1996) have significantly lower peak tension (~25%), and substantially slowed half relaxation time (~30%) in females compared to males. While modelling studies suggest that an increase in twitch contraction time improves FS (see Fig 9, Dideriksen et al. 2012), most

experimental studies indicate that there is little relationship between whole muscle contractile properties and FS for short-duration contractions. Since age-related contractile change is substantial and shows little relationship to FS, it is difficult to understand how moderately slower contractile properties in females compared to males would contribute to altering short duration steady force output between the sexes.

Motor unit number: The net force output of a muscle is resultant to the properties of the individual motor units (MU) and behaviour of the MU population, and thus, early speculation on FS considered individual as well as population MU characteristics. Animal studies have identified greater innervation ratios (~29%), alpha (α) and gamma (γ) motoneurons (~12%) and overall number of motor units (~10%) in the medial gastrocnemius of male compared with female rodents (Celichowski and Drzymala-Celichowska 2007, Mierzejewska-Krzyzowska et al. 2011, 2014). Although testosterone and estrogen have widespread effects on nerve and muscle (Sipilä et al. 2015), the challenge of MU counts being posthumous has limited comparative studies of human females and males. To our knowledge, Yuan et al (2000) is the only comparative study using 16 male and 21 female human cadaver spinal cords. At levels C5 and L3 motoneurons were larger in males than females, but numbers were similar between the sexes.

To surmount posthumous direct quantification of MUs, various estimation techniques have been applied in humans. Most use a general concept for MU number estimation (MUNE) and two (Yerdelen et al. 2006, Gawel and Kostera-Pruszczyk 2014) have compared the estimated MU numbers between females and males. These studies show no differences between the sexes, but suggest that the age-related decline in the number of MUs was greater in females compared with males for small muscles of the hand. The challenge with assessing sex-dependent differences in MU number relative to age-related decline is that biological age is connected to

occupational and leisure pursuits, which influence MU numbers with aging, as identified in the neuroprotective effect of life long use (Côté 2012, Power et al. 2012). More studies are needed to understand MU numbers across young and old females and males to establish whether age might preferentially reduce or protect MUs in one sex.

Although comparative MU physiology between the sexes is lacking, and needs to be defined, it is unlikely that absolute difference in MU number will be sufficient to alter FS. Many modelling and experimental studies, albeit not exclusive (Hamilton et al. 2004), suggest that a reduction in the number of MUs as well as discharge rate variability influences force steadiness (Enoka et al. 2003, Taylor et al. 2003, Dideriksen et al. 2012). However, more recent studies suggest that the contribution from the total available pool of motoneurons is a more likely contributor to FS, rather than absolute MU number (Farina & Negro 2015).

Likely Factors to Consider

The motor neuron pool, through the transmission of effective synaptic signals, contributes to force control through size-dictated MU recruitment and modulation of discharge rates. The intrinsic properties of motoneurons determine how synaptic inputs, arising from descending pathways, spinal interneurons and peripheral afferent feedback are transformed into action potentials that generate contractile force. These intrinsic properties as well as modulation of the motoneuron pool are associated with alterations in FS (Enoka et al. 2003, Mottram et al. 2005, Christou and Enoka 2011).

Types of Motor Units: Animal and human data suggest that motoneurons are larger in males than females (Yuan et al. 2000, Mierzejewska-Krzyzowska et al. 2014). The soma of larger alpha motoneurons have lower input impedance and greater electrical capacitance than smaller ones

and exhibit shorter hyperpolarization periods culminating in a greater voltage output and these characteristics are associated with greater levels of synaptic noise. This element of greater motoneuron size, that might increase CV of force, is offset by a higher number of motoneurons. Animal models suggest males have ~13% more alpha motoneurons (Mierzejewska-Krzyzowska et al. 2014), and this increase in number of MUs reduces CV of force, potentially through reductions in independent input, and enhances the effective common neural drive (Taylor et al. 2003, Hamilton et al. 2004, Farina and Negro 2015). Generally, there seems to be a compensatory counterbalance between motoneuron size and MU number in males that favors steady force output that requires further consideration.

In females a greater number of low-threshold MUs with a narrower recruitment range (Kukulka and Clamann 1981) would likely favor spatial filtering at low forces. In support of this premise of low-threshold MUs we have demonstrated lower recruitment thresholds in the female biceps brachii compared to males (Harwood et al. 2014). Inasmuch as smaller motoneurons of females are likely to have better filtering capacity to buffer independent oscillations of noise, these neurons also have persistent inward currents which exhibit little decay with time (Heckman and Enoka 2012). This effect is highlighted by the relatively greater increase in CV of force in females under stress-induced situations (Noteboom et al. 2001, Christou et al. 2004, Vanden Noven et al. 2014, Pereira et al. 2015) potentially arising from a longer-lasting catecholamine effect on the smaller motoneurons (Christou et al. 2004, Pereira et al. 2015) that influence sex-related differences in experiential responses to stress that influence functional output. Thus, in females the small low-threshold units should add a filtering effect, but this potential is mitigated by a smaller total pool of motoneurons that are more influenced by catecholamines. Ironically, it seems that in both females and males there is a paradox of MU size and MU number which

requires further evaluation. To-date, no human study has clearly assessed the inherent properties of motoneurons relative to sex-related differences in FS and how motoneuron output minimizes independent noise and transmits common elements to effect FS in females and males. Furthering the complexity of the concepts of independent and common synaptic input, Yoon et al. (2014) suggested that brain activation in isometric tasks, as measured with magnetic resonance imaging, does not contribute to neuromuscular noise in females and males. More studies are needed to evaluate the supraspinal contributions to females having higher CV of force than males.

Physiological and morphological differences in MU size and number between females and males from animal studies, offer insight into potential sources of neuromuscular noise. Yet, extrapolation leads to contradictory speculation as to the underlying cause of females having higher CV of force. To clearly address potential contributions of motoneuron size, and total number of active MUs to FS, more experimental MU studies are required in human females and males. Subsequently, FS modelling can be expanded to explore sex-related differences. Motoneurons might undergo compensatory adaptations between neural elements that alter the filtering of independent noise relative to effective common output; this requires consideration through experimental and modelling studies.

Motor unit discharge rate: Single MU recordings of interspike intervals, as well as decomposition from surface EMG multiple-array electrodes indicate that the variability of MU discharge rates, and particularly those at low frequencies (1-2Hz) describe ~70% of the variance in force fluctuations in young adults, most notably at low forces (Jesunathadas et al. 2012, Farina and Negro 2015). Very few studies have quantified MU activity in females and males, and fewer have explored the contributions of discharge rate and variability to sex-related differences in FS.

In animal and human models MU discharge rates were slightly higher in males compared with females (English and Widmer 2003, Harwood et al. 2014) and at a relative contraction intensity low-threshold MUs discharge at greater rates than high-threshold units (De Luca et al. 1982). The ~6% higher MU discharge rates reported at 15% MVC in males likely arise from a smaller number of low threshold MUs contributing to the isometric task (Harwood et al. 2014). To-date no study has reported the relative force-MU discharge rate relationship between females and males, and this would lend insight into the contribution of MUs to average discharge rates in females and males.

Studies are equivocal on how reflex modulation differs between sexes (Johnson et al. 2012, Vickery and Smith 2012). Although studies report both increases and decreases in amplitude and rate modulation there is a common element of agreement; the input-output pathway differs between males and females. This directional uncertainty of change in reflex behaviour between males and females might arise from experimental and methodological differences between studies; however, motoneurons receive excitatory and inhibitory inputs from afferents, interneurons and supraspinal centres, and the elements transferred as neural drive to the muscle are the common input elements (Taylor et al. 2003, Dideriksen et al. 2012, Farina and Negro 2015) and these might differ between the sexes.

Agonist and Antagonist Activity: Population factors such as nonuniform activation of agonist muscles, or alternating activity between agonist and antagonist muscles have been considered in the study of sex-related differences in FS. In low-force short duration isometric contractions, coactivation does not differ between females and males and was not a factor in sex-related

differences in FS (Brown et al. 2010, Harwood et al. 2014). In complex movements and conditions of injury or over-use, co-activation may interplay with muscle fatigue and influence steady force output (Fedorowich et al. 2013). Generally in isometric contractions there is little evidence of agonist-antagonist muscle interactions contributing to FS in the time domain, but greater consistency of evidence was observed in the frequency domain (Enoka et al. 2003, Dideriksen et al. 2012, Harwood et al. 2014). It appears modulation of the frequency content of agonist and antagonist EMG signals may represent a mechanism where opposing muscles become uncoupled and contribute to reduced FS (Golomer and Dupui 2000). We have reported dissimilar activation patterns between pairs of muscle synergists and antagonists for the elbow flexors, and through application of a vibratory stimulus to alter intermuscular coherence we identified that uncoupling of common oscillatory input may be responsible for reductions in FS (Harwood et al. 2014). However, the higher coherence between synergist muscle pairs in females compared with males did not fully account for the sex-related difference in FS.

To further explore intermuscular coherence between agonist and antagonist EMG, we strength matched females and males. Preliminary data indicate females were ~20% steadier than males (Figure 2A) and the spectral density estimates of the 8 – 12 Hz frequency bandwidth of force were higher in males than females at all forces and increased relative to target force. The increase in magnitude of the oscillations of the force signal relative to the target intensity was expected, yet the observation of lower power in the tremor bandwidth of females strength matched to males is a novel finding and requires further exploration. From this early data, as well as prior studies that reported greater EMG coherence among synergist muscles associated with increased force fluctuations (Danna-Dos Santos et al. 2010, Kattla and Lowery 2010) it is likely that muscle coherence is associated with the spectral density estimates of the force.

Agonist-antagonist and agonist-agonist coherence may represent mechanisms by which sex-related differences in FS occur and should be considered in future studies.

Strength: An obvious difference between sexes is males are stronger than females (Table 1) and this sex-related difference, which is unequal between muscles, is also evident when normalized to physiological cross-sectional area (Behan et al. 2018). Difference in strength are important as the maximal force capacity of a muscle influences the magnitude of force fluctuations (Brown et al. 2010, Harwood et al. 2014, Herring-Marler et al. 2014, Smart et al. 2018); however, both males and females exhibit the hyperbolic inverted “J” relationship across forces. This graphical representation was suggested to rely on the composite activity of the total pool of motoneurons (Taylor et al. 2003). With the exception of the hip extensors and flexors (Gruntz et al. 2010) lower absolute strength contributes to young females having a higher CV of force than males. Interestingly, the large difference in CV of force between young females and males is lessened with age (Tracy and Enoka 2002, Pereira et al. 2015). The mitigation of the sex-related difference in FS with age is surprising given that older females have higher levels of functional disability than males (Rantanen et al. 1999). This age-related sex-dependent change is likely associated with strength, as differences in MVC become less between females and males with age (Table 1).

When strength is matched (maximal strength is not different between sexes) FS results are inverted; females are steadier than males (unpublished data, Figure 2A). While strength matching does control for known differences in absolute strength and potential differences in agonist and antagonist activity contributions, the caveat is physical activity which is often contextualized around occupation and recreation pursuits that are likely gendered. Moreover,

matching strength between females and males does pre-establish a training influence on FS (Enoka et al. 2003) and likely a sampling bias. To match females and males for strength, the comparative involves a highly active group of females, or a very inactive and generally ‘weak’ group of males relative to population norms. Physical activity requires attention as maximal strength is a major contributor to FS and resistance training along with activities that involve motor coordination enhance FS (Hart and Tracy 2008). Given that differences in maximal strength result in relative target forces being held at heavier (lighter) absolute loads in males (females), and that FS differs across loads, it is clear that strength should be considered in future evaluation of FS between females and males.

[Insert Figure 2 Approximately here]

Tendon Properties: Tendons have received little attention in the investigation of FS. Although it was suggested from experimental and modelling studies that peripheral neuromuscular factors do not contribute to the underlying signal dependant noise of isometric contractions (Jones et al. 2002), the tendon was overlooked. When muscle tissue stiffness is low, fluctuations can be absorbed within the muscle to enhance steady hand control. In studies of age-related decline in FS, experimental data suggests that the tendon plays a key role in isometric FS (Johannsson et al. 2015, Smart et al. 2018) and functional movement (Onambélé et al. 2006). The inherent viscoelastic properties of tendons, whereby the tendon temporarily deforms in response to forces placed on it through the muscle creates a transient state that is likely to influence the transfer of force between muscle and bone in the production of steady force output.

The influence of the tendon's mechanical properties on FS were specifically evaluated in the Achilles (Johannsson et al. 2015) and distal biceps brachii (Smart et al. 2018) tendons during isometric plantarflexion and elbow flexion, respectively. Stiffness is the resistance of a tendon to elongate under load and increases with strength. Tendons that elongate less per applied force are in essence 'stiffer', and this was associated with a steadier and more efficient transfer of force from muscle to bone (Onambélé et al. 2006, 2007, Smart et al. 2018). As well, Young's modulus (YM), a normalized measure of tendon stiffness, was greater in the Achilles tendon of males compared to females and the changes in stiffness contributed to enhancing plantarflexion FS (Johannsson et al. 2015). Higher Achilles tendon compliance in females also contributed to slower fascicle shortening and greater tendon lengthening compared to males (Simpson et al. 2016, 2017). Generally, slower fascicle shortening may impair force transmission from the muscle to bone and reduce the accuracy with which force can be smoothly adjusted to maintain FS. The sex-related differences in tendon properties, and notably females being less stiff than males interestingly parallels observations of older adults being less stiff and having a higher CV of force relative to young (Smart et al. 2018). Overall, the tendon is more than just a passive contributor and further study will lend insight into peripheral factors that influence afferent feedback and in turn neuromuscular noise which contributes to females having a higher CV of force than males (Table 1; Figure 1).

Lower tendon stiffness in females compared to males (Onambélé et al. 2007, Johannsson et al. 2015) could be attributed to higher estrogen levels in females (Hansen and Kjaer 2016). Higher levels of estrogen in the ovulatory phase leads to lower muscle - tendon stiffness compared to the menses phase when estrogen is lowest (Eiling et al. 2007). This effect of estrogen challenges the study of sex-related differences as physiological properties vary across

the menstrual cycle. Hormonal levels between females and males are more similar (menses) or dissimilar (ovulatory) across the menstrual cycle and to properly account for sex differences (or lack thereof) the phase of the menstrual cycle should be identified. This is important for evaluating the tendon, as well as muscle strength and motor unit activity. Results vary as to the phase of the menstrual cycle where strength is greatest and motor unit activity highest (Sarwar et al. 1996) and this is, in-part, attributable to diurnal hormonal rhythms and the time-of-day testing occurs (Bambaeichi et al. 2004). The literature is equivocal, but the variability in the data lends substantive evidence to suggest studies of sex-related differences in FS would be enhanced through consideration of the menstrual cycle.

Conclusion

There is clear and growing literature that FS, is less in females compared with males when operationalized as CV of force. Despite the strong evidence of sex-related differences in neuromuscular morphology and physiology, few studies have directly explored the mechanisms that contribute to sexually dimorphic behaviour in FS. Mechanisms that augment neuromuscular noise and lessen steady force output more in females compared to males are not easily distinguishable from current studies. However, an evaluation of sex-related physiology in tandem with results from FS studies suggest that differences in fibre type, contractile properties, and absolute number of MUs are unlikely contributors. Strength is a prime factor to consider in understanding differences in FS between females and males. Strength likely influences FS directly as well as indirectly through other factors such as tendon mechanics and agonist-antagonist muscle activity. These interactions necessitate quantification of strength alongside other elements within one study. The MU is a key consideration for influencing neuromuscular

390 noise through the transfer of effective common elements and the filtering of independent noise
391 influencing FS. In both females and males there is a paradox of MU type and population
392 behaviour of active MUs which requires direct study relative to FS. Overall, the underlying
393 mechanisms influencing neuromuscular noise and contributing to females having a higher CV of
394 force than males is undistinguishable, yet there is consistent evidence to indicate that FS is
395 sexually dimorphic, and this requires further consideration.

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397 **Conflict of Interest**

398 The authors have no conflicts of interest to report.

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Legends

Figure 1: (A) Elbow flexor force steadiness in females (open symbols) and males (closed symbols). (B) Coefficient of variation for force in submaximal efforts in females (open bar) and males (closed bar). Each bar is an average of all studies and isometric tasks at each force level and the number (n) of data points included in the calculation of the mean coefficient of variation is presented. (C) Differences in coefficient variation of force between females and males for seven isometric tasks averaged across all force levels. Sources for data include: Almuklass et al. 2016, Brown et al. 2010, Christou et al. 2004, Clark et al. 2005, Harwood et al. 2014, Grunte et al. 2009, Pereira et al. 2015, Tracy and Enoka 2002, Yoon et al. 2014. CV, coefficient of variation; MVC, maximal voluntary contraction; PG: pinch grip; WE: wrist extension; EF: elbow flexion; HE: hip extension; HF, hip flexion; KE, knee extension; DF, dorsi-flexion.

Figure 2: (A). Unpublished data from the elbow flexors highlighting that when MVC is matched between males and females (inset) CV of force in females is less than males (8 females, 8 males 19-25yrs). (B). Published data demonstrating when CV of force is plotted relative to MVC there is a strong and significant relationship indicating that maximal strength influences FS (Figure 4 from Brown et al. (2010)). Open circles, females; Closed circles, females. Values are mean ± SE. CV, coefficient of variation; MVC, maximal voluntary contraction; N, Newtons. *, Males differ from females (p<0.05).

Table 1: Studies evaluating influence of sex on force steadiness

Reference	Experimental Groups: (Number of subjects, Age)	Task	Female MVC (%Males)	Target Force(s) (%MVC)	Female CV of Force (%Males)
Almuklass et al. 2016	Young Males (15, 24y) Young Females (15, 24y)	Wrist Extension	68	5	146
		Pinch Grip & Index Finger Abduction	(Handgrip)	10	152 NS NR
Brown et al. 2010	Young Males (8, 21y) Young Females (8, 22y)	Elbow Flexion (With three forearm orientations: Supinated; Neutral; and Pronated)	55; 57; 63	2.5	249; 255; 166
				5	204; 188; 133
				10	153; 176; 166
				25	200; 153; 203
				50	218; 172; 117
				75	176; 147; 114
Christou et al. 2004	Adult Males (18, 19-86y) Adult Females (18, 19-86y)	Pinch Grip	59	2	134
Clark et al. 2005	Young Males (11, 26y) Young Females (14, 23y)	Knee Extension	80	25	81 – first phase of a fatiguing contraction
Endo & Kawahara 2011	Young Males (30, 23y) Young Females (30, 24y)	Index Finger Extension, Abduction, Precision Grip		NR	63 – averaged across the three tasks
				NR	
Grunte et al. 2009	Young Males (10, 25y) Young Females (10, 23y) Old Males (11, 67y) Old Males (11, 64y)	Hip Extension	69; 72	0.06	
		Hip Flexion	64; 71	5	200; 300
				25	191; 103
				50	165; 89
Harwood et al. 2014	Young Males (8, 21y) Young Females (8, 22y)	Elbow Flexion	53	5	150; 132
				25	103; 112
				50	123; 89

Hunter & Enoka, 2001	Young Males (7, 26y)	Elbow Flexion	45	20	NS for Elbow Flexion NR
	Young Females (7, 28y)	FDI	67		
Pereira et al. 2015	Young Males (18, 20y)	Elbow Flexion	62; 48	5	100; 100
	Young Females (18, 20y)			30	100; 101
	Old Males (13, 70y)			40	100; 100
	Old Females (17, 70y)				
Ranganathan et al. 2001	Young Males (13, 27y)	Pinch Grip (index)	88; 84	5	NS
	Young Females (14, 27y)			10	NR
	Old Males (12, 71y)			20	
	Old Females (16, 71y)				
Svendsen & Madeleine 2010	Young Males (10, 25y) Young Females (10, 26y)	Elbow Flexion	55	10	NS
				20	NR
				30	
				40	
				50	
				60	
				70	
				80	
				90	
Tracy & Enoka 2002	Young Males (10, 22y)	Knee Extension (Young; Old)	77; 35	2	107; 77
	Young Females (10, 21.5y)			10	108; 88
	Old Males (10, 70y)			50	89; 82
	Old Females (10, 72y)				
Vanden Noven et al. 2014	Young Males (8, 20y)	Dorsiflexion	Female < Male NR	30	Female > Male NR
	Young Females (9, 20y)				
	Old Males (9, 69y)				
	Old Females (8, 69y)				
Yoon et al. 2014	Young Males (6, 27y) Young Females (8, 27y)	Dorsiflexion	79	10	98
				30	119
				50	120

F; female; M; male; y; years; NS; not significant statistically was reported and data was not provided in text, table or figures; NR, not reported

Draft

Figure 1: (A) Elbow flexor force steadiness in females (open symbols) and males (closed symbols). (B) Coefficient of variation for force in submaximal efforts in females (open bar) and males (closed bar). Each bar is an average of all studies and isometric tasks at each force level and the number (n) of data points included in the calculation of the mean coefficient of variation is presented. (C) Differences in coefficient variation of force between females and males for seven isometric tasks averaged across all force levels. Sources for data include: Almuklass et al. 2016, Brown et al. 2010, Christou et al. 2004, Clark et al. 2005, Harwood et al. 2014, Grunte et al. 2009, Pereira et al. 2015, Tracy and Enoka 2002, Yoon et al. 2014. CV, coefficient of variation; MVC, maximal voluntary contraction; PG: pinch grip; WE: wrist extension; EF: elbow flexion; HE: hip extension; HF, hip flexion; KE, knee extension; DF, dorsi-flexion.

232x187mm (300 x 300 DPI)

Figure 2: (A). Unpublished data from the elbow flexors highlighting that when MVC is matched between males and females (inset) CV of force in females is less than males (8 females, 8 males 19-25yrs). (B). Published data demonstrating when CV of force is plotted relative to MVC there is a strong and significant relationship indicating that maximal strength influences FS (Figure 4 from Brown et al. (2010)). Open circles, females; Closed circles, females. Values are mean $\pm$ SE. CV, coefficient of variation; MVC, maximal voluntary contraction; N, Newtons. *, Males differ from females ($p < 0.05$).

211x102mm (300 x 300 DPI)