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Amount and structure of force variability during short, ramp and sustained contractions in males and females

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ABSTRACT

The aim of this study was to investigate the effect of gender differences on force variability as assessed by means of linear and non-linear estimators during short duration, ramp and sustained isometric elbow flexions. Ten males and ten females performed elbow flexion receiving visual feedback from the direction of force exertion. Isometric elbow flexions were performed during: maximum voluntary contraction (MVC before and after endurance test), short contraction at 10–90% MVC with 10% increment for 5 s, ramp contraction from 5% to 50% MVC over 30 s, and endurance contraction at 20% MVC. Standard deviation (*SD*), coefficient of variations (*CV*), and sample entropy (*SaEn*) were computed from the force signals recorded in 3D. During short and ramp contraction, *SD* increased with contraction level while *SaEn* followed an inverted U-shape function ($p < .01$). During endurance test, *SD* and *CV* increased with contraction time ($p < .01$). *SD* and *SaEn* were consistently higher in males than females while it was opposite for *CV* ($p < .05$). Separate control and compensatory mechanisms could be responsible for the observed changes in the amount and structure of task-related and tangential forces variability. Moreover, gender differences most likely point towards gender-dependent force control mechanisms. The lower magnitude and structure of variability observed in females may increase the risk of muscle overload and damage.

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1. Introduction

The study of gender differences with respect to for instance pain and motor control has attracted a lot of interest within the last decade (Greenspan et al., 2007; Semmler, Kutzscher, & Enoka, 1999). Differences in factors like muscle mass, muscle morphology, substrate utilization, and neuromuscular activation have been reported among males and females (Hicks, Kent-Braun, & Ditor, 2001; Krogh-Lund & Jørgensen, 1991; Sejersted et al., 1984). A larger muscle mass concomitant to the increased strength (Miller, MacDougall, Tarnopolski, & Sale, 1993) could result in larger increased intramuscular pressure in males compared with females. Thus, metabolic imbalance between supply and demand may occur, resulting in a greater rate of fatigue development in males (Béliveau et al., 1992; Sahlin, Cizinsky, Warholm, & Höberg, 1992). Further, females are found to be more fatigue-resistant than males during relative endurance tasks at sub-maximal force level (Maughan, Harmon, Leiper, Sale, & Delman, 1986; Semmler et al., 1999). Contradictory results are reported in studies testing gender difference in strength-matched groups. For instance, no difference between genders is found in line with the hypothesis that intramuscular pressure and muscle mass play a role (Clark, Manini, Thé, Doldo, & Ploutz-Snyder, 2003; Hunter & Enoka, 2001), while other studies have shown opposite results arguing for a less potent effect of metabolic imbalance (Hunter, Critchlow, Shin, & Enoka, 2004b; Larivière et al., 2006).

In addition to muscle mass and morphology, neuromuscular activation, and coordination have been suggested as important factors but only a few studies have examined this issue (Beck et al., 2005; Ge, Arendt-Nielsen, Farina, & Madeleine, 2005; Sung, Zurcher, & Kaufman, 2008). An altered neuromuscular activity is reported to lead to improved recovery period for the deactivated motor units during endurance contraction (Fallentin, Jørgensen, & Simonsen, 1993; Hunter & Enoka, 2003), and this mechanism could be more potent for females compared with males explaining difference in an endurance task (Semmler, Kutzscher, & Enoka, 2000). Finally, both peripheral and central mechanisms are likely to explain gender differences during sustained contraction.

Fluctuation in a recorded signal has in general been perceived as noise and disturbance to the signal of interest (Fitts, 1954; Schmidt, Zelanik, Hawkins, Frank, & Quinn, 1979). In studies investigating force control, force fluctuation or variability can be a way to assess important aspects of motor control (Jordan & Newell, 2004; Latash, Scholz, & Schöner, 2002). As previous studies have indicated, variability is not random like noise, but exhibit a degree of order that can be attributed to the operation of an adaptive control system (Slifkin & Newell, 1999). Nonlinear analysis derived from nonlinear dynamics and chaos theory is a valuable approach to understand the underlying aspects of neurophysiological signals (Heffernan et al., 2009; Richman & Moorman, 2000; Slifkin & Newell, 1999; van Emmerik & van Wegen, 2002). The structure of variability is usually measured by computing for instance the approximate entropy of the force signal (Heffernan et al., 2009; Slifkin & Newell, 1999; Sosnoff, Valantine, & Newell, 2006).

Hong, Lee, and Newell (2007) have recently shown during short duration contractions that compensatory mechanisms are governing the amount and structure of variability between dimensions, i.e., task-related force and tangential forces. To our knowledge, no studies have investigated the amount and structure of force variability in task-related and tangential forces during discrete and continuous force production. Moreover, linear methods have mainly been used to assess variability in genders during, for instance, sustained contraction (Hunter & Enoka, 2001) and only one study has reported unexpected higher entropy values for males than for females (Sung et al., 2008). This calls for further studies describing the structural changes of force variability in task-related and tangential forces in relation with respect to gender difference during short and continuous force production.

In the present study, we hypothesized gender differences in the magnitude and structure of force variability in task-related and tangential forces. For this purpose, we examined the effect of gender on force variability in 3D during short duration, ramp and endurance contractions. Gender comparison was assessed by means of linear and nonlinear methods during discrete and continuous isometric elbow flexion.

2. Materials and methods

2.1. Participants

Ten males and ten females participated in the study after having given their informed consent. The participants' anthropometric information is shown in Table 1. All participants were healthy and without any known neurological disorders. The study was approved by the local ethics committee (N-20070004MCH) and conducted in conformity with the Declaration of Helsinki.

2.2. Experimental procedure

The participants performed isometric elbow flexion consisting of short duration contractions, ramp contraction, and endurance contraction. The forces were recorded in 3D: (1) Task-related force: *Fx*: mainly elbow flexion and wrist flexion. (2) Tangential forces: *Fy*: mainly shoulder flexion, and *Fz*: mainly external shoulder rotation and radial deviation of the wrist. During the recordings, participants were sitting on a chair and holding the force sensor with the palm towards the ceiling and the elbow flexed at 90° (Fig. 1). The wrist and the shoulder were maintained in neutral position and the arm was in contact with the chest (slight touch). The experimenter controlled the participant position throughout the experiment.

The experiment consisted of:

1. Maximal voluntary contraction (MVC_{init}) of *Fx* was recorded three times to determine the participants' maximum elbow flexion force. Each trial lasted 3 s and was separated by a 2 min pause.

Table 1
Participants information (mean ± SD).

	Females	Males
Age (years)	24.7 ± 3.9	25.8 ± 2.5
Weight (kg)	65.8 ± 9.3	80.2 ± 7.0
Height (cm)	170 ± 7.7	188.9 ± 7.2
Body mass index (kg/m^2)	22.6 ± 2.4	22.5 ± 1.2

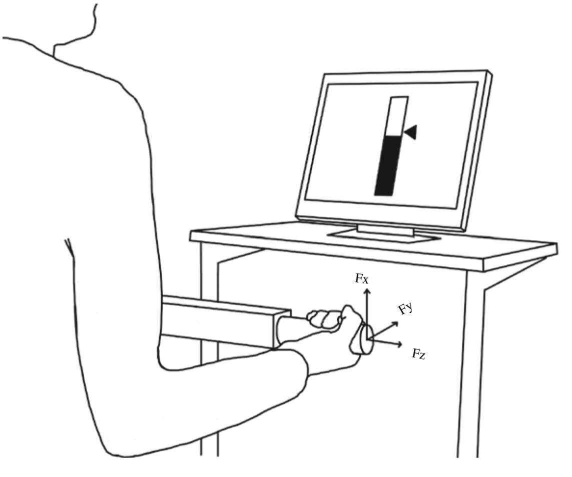

Fig. 1. Experimental setup depicts a participant performing an isometric elbow flexion (short duration contractions, ramp contraction, and endurance contraction,. Forces were recorded in 3D. Task-related force (*Fx*: mainly of elbow flexion and wrist flexion) and tangential forces (*Fy*: mainly of shoulder flexion and *Fz*: mainly shoulder rotation and radial deviation of the wrist).

MVC$_{init}$ of *Fx* was used as reference contraction to set sub-maximal levels. Verbal encouragement was given during MVC tests. Participants rested for 2 min after MVC recordings.

2. Short duration contractions consisted of nine contractions ranging from 10% to 90% of MVC$_{init}$ of *Fx* with a 10% increment in between (Fig. 2). The order of the contractions was randomized to prevent a priori knowledge of the following contraction level. Each contraction lasted 5 s with a 30 s pause in between. The participants were asked to reach the desired contraction level as fast as possible. Participants rested for 2 min after short duration contractions.
3. Ramp contraction lasted 30 s starting at 5% and reaching 50% MVC$_{init}$ of *Fx* (slope of 1.5% MVC/s; Fig. 2). Participants rested for 2 min after ramp contraction.
4. Endurance contraction: The participants maintained a level corresponding to 20% MVC$_{init}$ of *Fx* until task failure (Fig. 2). Task failure occurred when the participants were not able to maintain force at 20 ± 2% MVC of *Fx* for more than 5 s. Verbal encouragement was also given during endurance test.
5. MVC$_{final}$ of *Fx* was recorded 30 s after endurance test to assess changes in maximum force with respect to MVC$_{init}$ of *Fx*.

For the short duration, ramp and endurance contraction, the task-related force *Fx* was visually fed back to the participants. The pixel/*N* ratio was 2.4 ± 0.8 pixel/*N*.

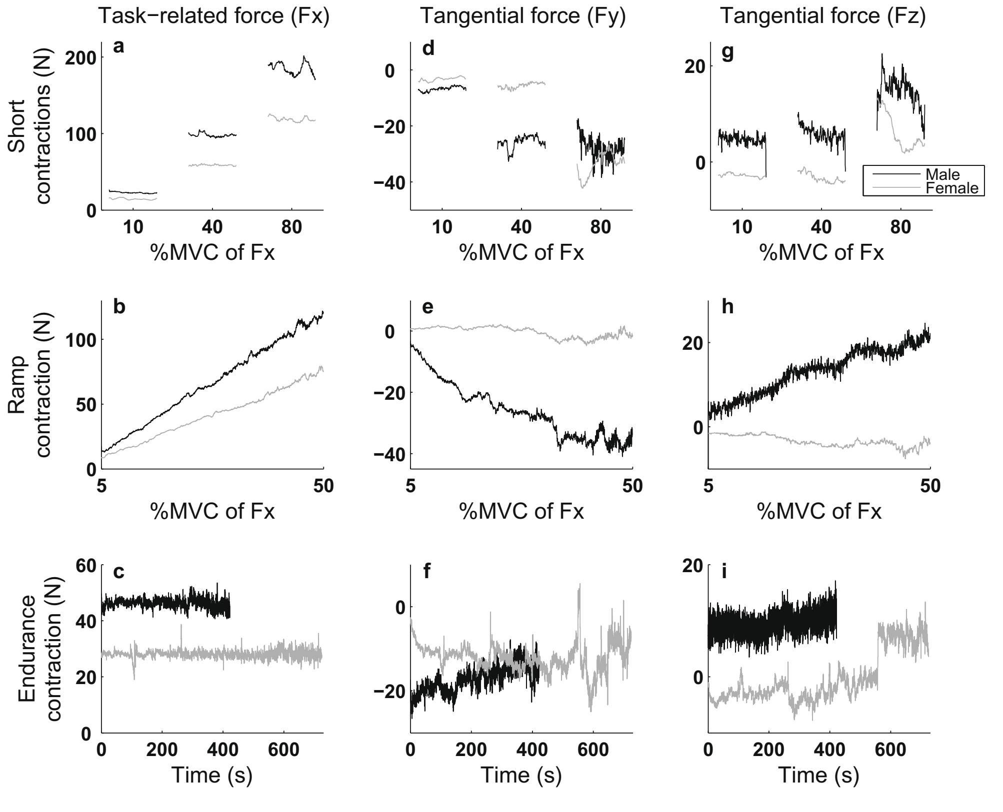

Fig. 2. Examples of 3D force traces for one male and one female. Task-related forces (*Fx*; 2a–c) and tangential forces (*Fy*; 2d–f and *Fz*; 2g–i) are shown for short duration (10%, 40% and 80% MVC of *Fx*), ramp (from 5% to 50% MVC of *Fx*), and endurance contractions (20% MVC of *Fx*).

2.3. Data analysis

The applied forces were measured in 3D (FS-6, AMTI, Watertown, MA, USA). Force signals were low-pass filtered (10.5 Hz) and amplified 1000 times. The signals were AD-converted (12 bits A/D converter, Nidaq 6024, National Instruments, Austin, TX, USA) and recorded through a custom made program in Labview 8.2 (National Instruments, Austin, TX, USA), which also provided force feedback to the participant. All signals were sampled at 500 Hz and saved for further analysis in MATLAB R2007a (The MathWorks Inc., Natick, MA, USA).

For MVC trials, the maximum force was computed over 1 s with 100 ms overlapping. The highest force was then considered as MVC of *Fx*.

The contributions of tangential forces (*Fy* and *Fz*) to the task-related force (*Fx*) were calculated as the percentage contribution of each tangential force compared to *Fx*.

The error of performance was calculated as the difference between the exerted force signal and the required force level in percent.

Linear analysis of the force signals was performed to quantify the amount of variability. Standard deviation (*SD*) and coefficient of variation (*CV*) were calculated. *SD* reflects the amount of the variability, and *CV* is the relative variability. *CV* was derived from the absolute value of the mean and *SD* of the signal.

Nonlinear analysis of the force signals was performed to assess the structure of variability. Time dependent structure of force variability reveals deterministic and stochastic organization of the neurophysiological system and the degree of complexity of a signal is typically associated with the number of system elements and their functional interactions (Heffernan et al., 2009; Jordan & Newell, 2004; van Emmerik & van Wegen, 2002). Sample entropy (*SaEn*) was computed for this purpose. *SaEn* expresses the complexity of the recorded signal (Kuusela, Jartti, Tahvanainen, & Kaila, 2002; Richman & Moorman, 2000). *SaEn* is the negative logarithm of the relationship between the probabilities that two sequences coincide for $m + 1$ and for m points, where larger value indicates more complex structure or lower predictability. The embedding dimension, m, and the tolerance distance, r, were set to $m = 2$ and $r = 0.2 \times SD$ of the force channel.

For the short duration contractions, *SD*, *CV*, and *SaEn* were calculated over 3 s epoch (discarding the first and last s) for each contraction level. Similarly for the ramp contraction, linear and nonlinear parameters were calculated over 3 s epochs through the 30 s contraction. Similarly, for the endurance contraction, seven epochs of 3 s from 0% to 100% of contraction time (steps of 16.7%) were used.

2.4. Statistical analysis

A one-way analysis of variance (ANOVA) with factor gender and dependent variable endurance time, a two-way ANOVA with factors gender and time (before/after endurance test) and dependent variable MVC level/tangential force contribution, and a three-way ANOVA with factors gender, contraction level/contraction time, and force direction and dependent variables error of performance, *SD*, *CV* and *SaEn*, were performed using SPSS 16.0 (SPSS Inc., Chicago, Illinois, USA). A post hoc test of least significant difference was used for pair wise comparisons. Mean ± *SD* is reported. The level of significance was set at $p < .05$.

3. Results

Males had higher MVC of *Fx* than females ($F = 70.9$, $p < .01$), respectively 245.6 ± 61.2 vs. 134.6 ± 25.8 N. MVC of *Fx* decreased from $\mathrm{MVC}_{\mathrm{init}}$ to $\mathrm{MVC}_{\mathrm{final}}$ ($F = 11.5$, $p < .01$), respectively from 212.5 ± 76.1 to 167.8 ± 63.6 N.

3.1. Contribution from tangential forces to the task-related force Fx

For the short duration contractions (Fig. 3a), the two-way ANOVA showed gender differences, males had larger contribution from tangential forces to *Fx* than females ($F = 14.2$, $p < .01$), respectively,

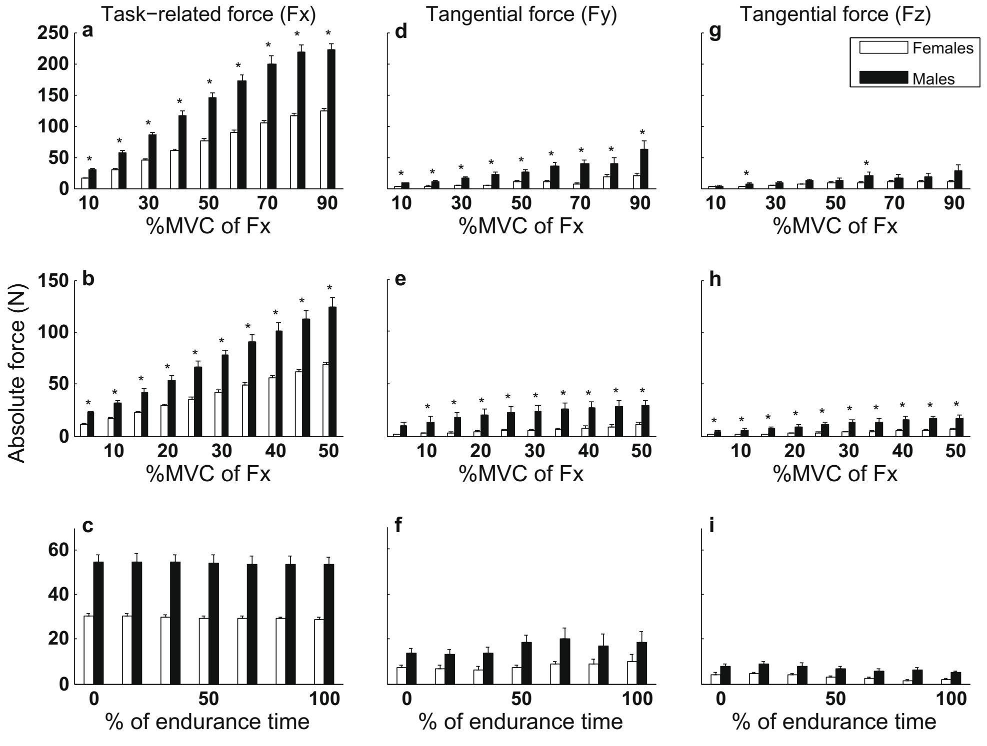

Fig. 3. Mean + SE force (*N*) for task-related force (*Fx*; 3a–c) and tangential forces (*Fy*; 3d–f and *Fz*; 3g–i) during (a) short duration contractions, (b) ramp contraction, and (c) endurance contraction. *Significant difference between genders ($p < .05$).

19.2 ± 7.9% vs. 11 ± 5.5%. *Fy* contributed significantly more than *Fz* to *Fx* ($F = 12$, $p < .01$), respectively 18.8 ± 9.2% vs. 11.3 ± 6.8%.

For the ramp contraction (Fig. 3b), the two-way ANOVA showed gender differences, males had larger contribution from tangential forces to *Fx* than females ($F = 5.2$, $p = .02$), respectively 30.1 ± 35.1% vs. 10.2 ± 7.6%. For the endurance contraction (Fig. 3c), *Fy* contributed significantly more than *Fz* to *Fx* ($F = 17$, $p < .01$), respectively, 31.2 ± 21.2% vs. 10.7 ± 5.2%.

3.2. Short duration contractions

The error of performance increased with increasing contraction level for short duration contractions (Fig. 4a; $F = 5.9$, $p < .01$) but did not change with gender ($F = 0.1$, $p = .76$). The three-way ANOVA showed gender differences or tendency towards differences, *SD* and *SaEn* were larger for males compared with females while it was the opposite for *CV* (Fig. 5; respectively $F = 93.0$, $p < .01$, $F = 5.2$, $p = .05$ and $F = 12.1$, $p < .01$). *SD* increased with increasing contraction level ($F = 48.7$, $p < .01$). *SaEn* also tended to increase and decrease with contraction level ($F = 5.2$, $p = .05$). *SD* was higher for *Fx* compared with *Fy* and *Fz* while it was the opposite for *CV* and *SaEn* (respectively, $F = 54.5$, $p < .01$, $F = 101$, $p < .01$ and $F = 25.9$, $p < .01$). Moreover, there was a significant Gender × Contraction Level interaction for *SD* ($F = 10.8$, $p < .01$). *SD* was higher for males compared with females at 10–20–30–40–50–70–80–90% MVC of *Fx* ($p < .01$). There was a significant Gender × Force Direction interaction for *CV* ($F = 7.5$, $p < .01$). *CV* was higher for females compared with males in *Fy* ($p < .01$). Finally, there was significant Contraction Level × Force Direction interaction for *SaEn* ($F = 1.9$, $p = .02$). *SaEn* was higher for *Fz* than *Fx* at 10–20–30–60–70–80–90% MVC of *Fx* ($p < .05$). *SaEn* was also higher for *Fz* than *Fy* at 10–20% MVC of *Fx* ($p < .02$) and for *Fy* than *Fx* at 60–70–80–90% MVC of *Fx* ($p < .01$).

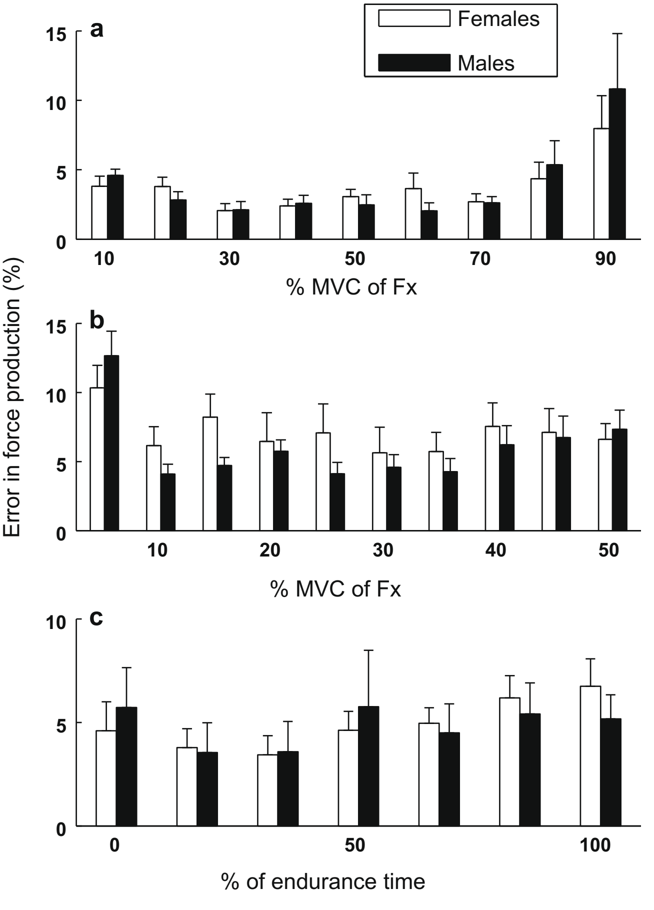

Fig. 4. Mean + SE error of performance (%) during (a) short duration contractions, (b) ramp contraction, and (c) endurance contraction.

3.3. Ramp contraction

The error of performance increased with increasing contraction level during the ramp contraction (Fig. 4b; $F = 4.0$, $p < .01$) but did not change with gender ($F = 0.6$, $p = .44$). The three-way ANOVA showed gender differences, *SD* and *SaEn* were larger for males compared with females while this pattern of results was the opposite for *CV* (Fig. 6; respectively, $F = 217.4$, $p < .01$, $F = 12.6$, $p < .01$, and $F = 26.2$, $p < .01$). *SD* and *SaEn* increased with increasing contraction level, while *CV* decreased (respectively, $F = 15.9$, $p < .01$, $F = 31.2$, $p < .01$, and $F = 3.4$, $p < .01$). *SD* was higher for *Fx* compared with *Fy* and *Fz* while it was the opposite for *CV* and *SaEn* (respectively, $F = 61.2$, $p < .01$, $F = 61.1$, $p < .01$ and $F = 136$, $p < .01$). There was a significant Gender × Contraction Level interaction for *SD* ($F = 2.5$, $p < .01$). *SD* was higher for males compared with females for all contraction levels ($p < .01$).

There was also a significant Gender × Force Direction interaction for *CV* ($F = 6.5$, $p < .01$). *CV* was higher for females compared with males in *Fy* ($p < .01$). There was a significant Contraction Level × Force Direction interaction for *SaEn* ($F = 2.0$, $p = .01$). *SaEn* was higher for *Fy* than *Fx* at 5–15–20–25–30–35–40–45–50% MVC of *Fx* ($p < .05$). *SaEn* was higher for *Fz* than *Fx* at all contraction levels ($p < .01$) and than *Fy* at 5–10–15–20% MVC of *Fx* ($p < .01$).

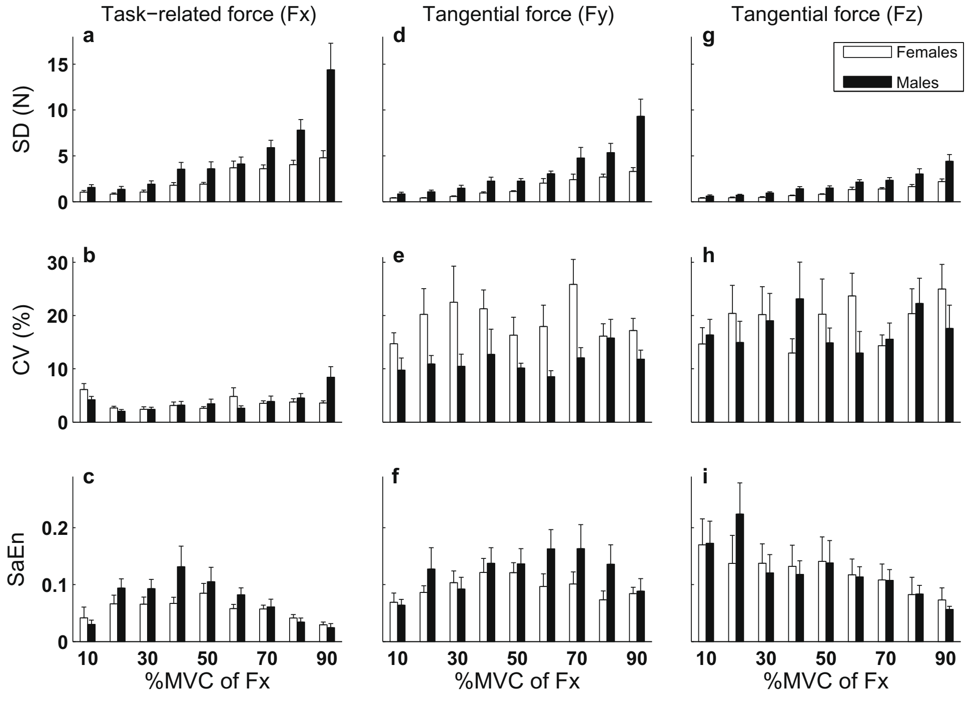

Fig. 5. Mean + SE standard deviation (*SD*, *N*), coefficient of variation (*CV*, %) and sample entropy (*SaEn*) for task-related force (*Fx*; 5a–c) and tangential forces (*Fy*; 5d–f and *Fz*; 5g–i) during short duration contractions.

3.4. Endurance contraction

The error of performance did not change during the sustained contraction (Fig. 4c; $F = 0.9$, $p = .50$) and nor with gender ($F = 0.01$, $p = .91$). Females had longer endurance duration than males, respectively, 682.8 s vs. 344.8 s ($F = 7.5$, $p = .01$). The three-way ANOVA showed gender differences, *SD* and *SaEn* were higher for males than females while it was the opposite for *CV* (Fig. 7; respectively $F = 186.2$, $p < .01$, $F = 5.0$, $p = .02$ and $F = 4.5$, $p = .03$). Both *SD* and *CV* increased with contraction time (respectively, $F = 34.1$, $p < .01$ and $F = 8.5$, $p < .01$). *SD* was higher for *Fx* compared with *Fy* and *Fz* while it was the opposite for *CV* and *SaEn* (respectively, $F = 30.0$, $p < .01$, $F = 141$, $p < .01$ and $F = 23.4$, $p < .01$). Moreover, there were significant Gender × Contraction Time, Gender × Force Direction and Contraction Time × Force Direction interactions for *SD* (respectively, $F = 4.1$, $p < .01$, $F = 3.3$, $p = .04$, and $F = 2.5$, $p < .01$). *SD* was higher for males compared with females throughout the contraction ($p < .01$). *SD* was also higher for males compared with females in all force directions ($p < .01$). *SD* was higher in *Fx* and *Fy* compared to *Fz* at 50–66.7–88.3–100% of contraction time. There was also a significant Contraction Time × Force Direction interaction for *CV* ($F = 2.2$, $p = .01$). *CV* was higher for *Fy* and *Fz* compared with *Fx* throughout the contraction time ($p < .01$) and *CV* was higher for *Fz* compared with *Fy* at 50–66.7–83.3–100% contraction time ($p < .01$).

4. Discussion

The primary goal of this study was to investigate the effect of gender differences in variability of task-related and tangential forces by means of linear (amount of variability) and nonlinear (structure of variability) analysis during voluntary short duration, ramp and endurance isometric elbow flexions. The findings revealed for the first time that gender played a role in force variability during short, ramp

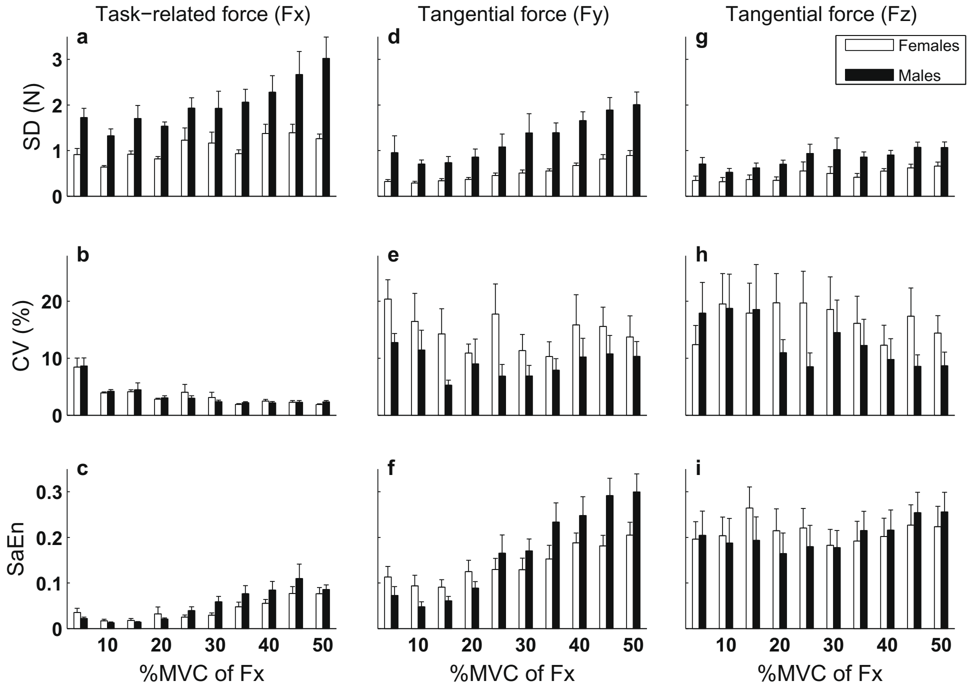

Fig. 6. Mean + SE standard deviation (*SD*, N), coefficient of variation (*CV*, %) and sample entropy (*SaEn*) for task-related force (*Fx*; 6a–c) and tangential forces (*Fy*; 6d–f and *Fz*; 6g–i) during ramp contraction.

and sustained contractions. Females were characterized by lower amount (*SD*) and structural complexity (*SaEn*) than males. Further, the amount of variability increased with contraction level while the structure of variability changed according to an inverted U-shape function in the task-related force and tangential force *Fy* during discrete contractions. Finally, the amount of variability also increased with contraction time in the task-related force and tangential force *Fy*.

4.1. Effect of contraction level and gender on force variability

For short duration and contractions, the observed changes in the amount and structure of variability are in line with previous results reporting an exponential increase in *SD* and a decrease in *CV* in the direction of force exertion (Hong et al., 2007; Slifkin & Newell, 1999; Tracy, Mehoudar, & Ortega, 2007). Similar to that, *SD* increased for both task-related and tangential forces during short and continuous contractions. *CV* remained low most likely due to failure in reaching the required level for the high sub-maximal contractions as depicted by the increase in error of performance. Moreover, *CV* decreased slightly during ramp contraction as expected due to the exponential increase in *SD* with linearly increasing forces (Hong et al., 2007; Sosnoff et al., 2006).

SD was larger for males than for females in the direction of force exertion but also in the tangential directions even though there were no differences in the error of performance. As expected, the results were opposite for *CV*. This confirmed that the variability in discrete force production is non-proportional to force level (Carlton & Newell, 1993). Moreover, the contributions of tangential forces to the task-related force were larger for males than for females during short duration and ramp contractions due to higher absolute force in males. This can in turn have influenced the magnitude of force variability (Hong & Newell, 2008; Vaillancourt, Larsson, & Newell, 2002) as there were gender differences in the pixel/*N* ratio. Furthermore, the larger amount of variability (*SD*) found in males compared with females could also indicate that males had an elevated activity in the biceps brachii muscle

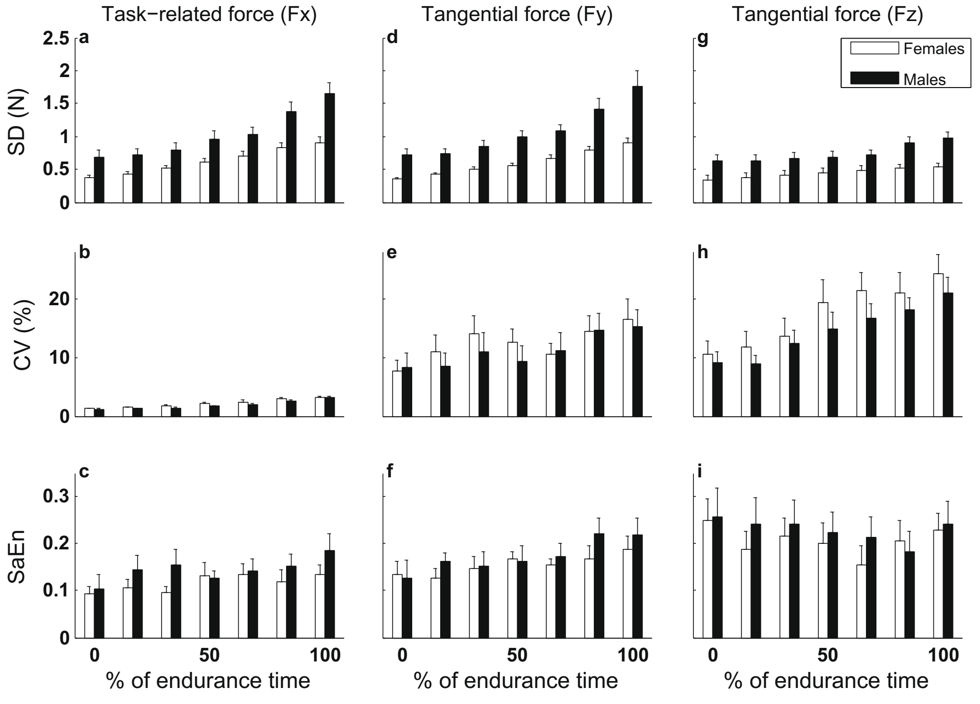

Fig. 7. Mean + SE standard deviation (*SD*, *N*), coefficient of variation (*CV*, %) and sample entropy (*SaEn*) for task-related force (*Fx*; 7a–c) and tangential forces (*Fy*; 7d–f and *Fz*; 7 g–i) during endurance contraction.

compared with females due to higher force level (Hunter & Enoka, 2001) and that muscle activation pattern could be different among genders (Ge et al., 2005; Yoon, Delap, Griffith, & Hunter, 2007).

With respect to the changes in the structure of variability, our results in the direction of force exertion are also in line with Slifkin and Newell (1999) and Hong et al. (2007). The sample entropy increased up to approximately 50% MVC of *Fx* during short duration contractions and then decreased, following an inverted U-shape (Hong et al., 2007; Slifkin & Newell, 1999). Compensatory synergistic mechanisms are likely to explain the similar changes in the task-related force and tangential force (*Fy*) seen during both discrete and continuous force production in line with a recent study (Hong et al., 2007). The sample entropy was higher for tangential forces than for task-related force. This confirmed recent results showing that the changes in approximate entropy values differ between task-related and tangential forces (Hong et al., 2007). Further, the present study emphasizes that the amount and structure of force variability during discrete and continuous contractions could be governed by separate control processes (Sosnoff et al., 2006).

Similar to the magnitude of variability, the complexity of the task-related and tangential forces were also higher for males than for females arguing for potential gender-dependent force control strategies. This would imply that the forces generated by males arise from a higher number of attractors or neural oscillators than females (Heffernan et al., 2009; Lipsitz, 2002; Slifkin & Newell, 1999; Sosnoff, Vaillancourt, & Newell, 2004; van Emmerik & van Wegen, 2002). Finally, the observed changes in the amount and structure of variability occurring in the task-related and tangential forces can be explained by a lack of control of the participants' dominant arm position and/or compensatory mechanisms like co-contraction and changes in agonist/antagonist relationship aiming at maintaining the same force output (Ervilha, Arendt-Nielsen, Duarte, & Graven-Nielsen, 2004; Hong et al., 2007; Reeves, Cholewicki, Milner, & Lee, 2008; Rudroff, Staudenmann, & Enoka, 2008). More studies assessing force variability in 3D are warranted to investigate neuromotor function.

4.2. Effect of endurance time and gender on force variability

The present study confirmed the presence of gender differences in endurance time (Hunter et al., 2004b; Maughan et al., 1986; Sato & Ohashi, 1989) even though similar endurance time have also been reported in strength-matched groups (Hunter, Critchlow, Shin, & Enoka, 2004a; Hunter & Enoka, 2001). The amount of force variability increased in task-related and tangential forces with contraction time while the level in error of performance did not change. The tangential force *Fy* contributed more than *Fz* to the task-related force showing that the exerted force was not kept purely mono-directional during the endurance test. Similar to what we observed during discrete and continuous contractions, the amount (*SD*) and structure (*SaEn*) were larger for males than for females during fatiguing isometric contraction while opposite results were obtained for *CV*. The results concerning gender effects are corroborated by recent studies from Yoon et al. (2007) and Sung et al. (2008).

Muscle fatigue is found to alter biomechanical movement patterns (Selen, Beek, & van Diëen, 2007). The present gender-dependency in the amount and structure of force variability during endurance contraction could be due to the discrepancies in muscle activation pattern (Ge et al., 2005; Hunter et al., 2004a, 2004b; Yoon et al., 2007). The level of muscular fatigue assessed by the decrease in MVC of *Fx*, immediately following endurance test was similar for males and females in line with Yoon et al. (2007). During sustained contraction, the CNS compensate for the decrease in the force generated by individual motor units by additional recruitment of motor units, changes in motor unit discharge rate and motor unit substitution (Gandevia, 2001). These mechanisms are likely to account for the difference in size and structure of force variability among genders during an endurance test. Similarly to our findings during short duration and ramp contractions, the control mechanisms influencing the amount and structure of force variability could be gender-dependent.

Moreover, the lower complexity or higher predictability found in females compared with males corresponding to a higher degree of regularity may not be favourable. Indeed, it may not allow appropriate adaptation to changes in sensory afferent feedback and may increase the risk for muscle overload and damage in females (Ge et al., 2005; Lipsitz, 2002; Madeleine, Mathiassen, & Arendt-Nielsen, 2008; Slifkin & Newell, 1999). While among males, the CNS may be better to take benefit of the redundancy of the motor system (Latash & Anson, 1996).

In summary, the analysis variability of task-related and tangential forces showed that the changes in the amount and structure of force variability differed with increasing contraction level and increased similarly with contraction time. This could be due to separate control processes and compensatory mechanisms influencing variability in task-related and tangential forces. Furthermore, the amount and structure of force variability was higher in males compared with females arguing for possible gender-dependent force control mechanisms.

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