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Forced ventilation increases variability of isometric finger forces

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Abstract

The study aimed to assess the effects of forced ventilation on variability of the index finger force at the submaximal levels. Fourteen (6 men, 8 women) healthy subjects were instructed to perform self-initiated forced inspiration and forced expiration, the Valsalva maneuver and normal breathing while sustaining 15%, 30%, and 45% of maximal voluntary contraction (MVC) by the index finger. Standard deviation (S.D.) of finger forces increased significantly with the level of force. At each level of force, the mean force was not significantly changed under different breathing conditions. S.D. and coefficient variation (CV) during forced inspiration and expiration was significantly greater than S.D. and CV during normal breathing and the Valsalva maneuver at each force level. No significant differences in S.D. and CV were found between forced inspiration and expiration or between normal breathing and the Valsalva maneuver. Force variability synchronized with the initiation of forced inspiration and expiration, but not with the ventilation data during the Valsalva maneuver or normal breathing. These findings demonstrate clearly that finger force variability is affected by specific ventilation patterns at submaximal force levels. Therefore, assessment of force variability should consider the influence of ventilation.

Keywords

force variability; isometric force; respiration; Valsalva maneuver; finger

Variability of force during continuous isometric contractions of muscles in both upper and lower extremities has been well documented [6,9,19,20]. The amount of variability (characterized by standard deviation; coefficient of variation) is closely related to force level. It has been generally accepted that there is a linear relationship between force level and variability over a moderate range of force levels [4,20]. The linearity, however, does not hold at the higher [6] and lower [21] range of the force spectrum. For example, Christou et al. [6] reported a sigmoid increase in the amount of variability (standard deviation) as a function of force level ranging from 2% to 95% maximal voluntary contraction (MVC).

The variability in continuous isometric force production is considered to be driven mainly by neurophysiological mechanisms. The proposed mechanisms include the unfused firing of motor units [11], the variability of the discharge rate [15,24] and the combination of both motor unit recruitment and firing rate modulation strategies [20,22]. A few other factors could also influence force variability, such as age [3,5], muscle groups [7], type of muscle contractions [3] and gain of visual feedback [21].

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Interactions between respiratory and motor functions are observed in a number of everyday tasks and skilled performance, such as simple limb movements, locomotion, and muscle strength [14,17,18,23]. For example, breathing altered the precision of visually-controlled step-tracking movements [18]. Finger tracking tasks were performed more precisely in mid-inspiration and mid-expiration than at the phase-transitions from inspiration to expiration or vice versa. In a recent study, Li and Laskin [14] reported that peak force increased significantly from forced inspiration to forced expiration (about 10% MVC). It was proposed [14] that enhanced activation in cortical respiratory centers, associated with initiation of forced respiration, acted in concert with the descending motor drive from the primary motor cortex to the exercising, non-respiratory finger flexors, resulting in the ventilation-associated increase in maximum muscle strength.

This proposed mechanism of respiratory-motor enhancement was expected to be held at submaximal levels of force production. As such, initiation of force ventilation would lead to greater fluctuations in force output, i.e., force variability during continuous isometric contractions at submaximal levels. The purpose of this study was to test this mechanism, specifically by examining the effects of breathing (normal breathing, forced inspiration, forced respiration, and the Valsalva maneuver) on force variability of index finger force over a moderate range (15%, 30%, and 45% MVC). We hypothesized that force variability (measured as standard deviation) would increase with the level of force and during forced breathing.

Fourteen recreationally active individuals (6 men, 8 women; age: 25.1 ± 2.9 years) participated in the present study. This study was approved by the University of Montana Institutional Review Board and all subjects gave written informed consent. All procedures were consistent with The Declaration of Helsinki.

The experimental protocol was similar to an earlier study [14]. Briefly, subjects sat on an adjustable chair, breathing through a facemask attached to a pneumotach system (Series 1110A; Hans Rudolph, Kansas City, MO) during the experiment. The right forearm of the subject was stabilized on a wooden board by two medio-laterally adjustable vertical aluminum bars. The subject placed his or her fingertips on four force sensors. Fingers were slightly curved (about 20° flexion of interphalangeal joints) such that finger forces were produced by pressing against the force sensors at fingertips isometrically while preserving the described configuration.

Subjects were asked to press against the force sensor as hard as they could with the index finger. The highest value of three attempts was chosen as the MVC of index finger. Three levels of target force were then created at 15%, 30%, and 45% MVC, respectively. The target level was indicated by a horizontal red on the computer screen. The full scale was fixed at 60% MVC.

Subjects were then instructed to press against the sensor with the index finger to generate and sustain an the index finger force to match the red line as best as they could under four different breathing conditions: (1) normal breathing: no specific instructions on breathing patterns, (2) forced inspiration: subjects were explicitly instructed to match the red line as best as they could while initiating a rapid, self-paced, forced inspiration, (3) forced expiration: similar to forced inspiration, but with forced expiration, and (4) Valsalva maneuver: subjects were explicitly instructed to match the red line as best as they could while performing the Valsalva maneuver. The Valsalva maneuver was usually self-initiated within 1~3 seconds after the index finger force reached the target line and stable.

Subjects relaxed their fingertips on the force sensors before a trial. After two computer-generated sounds, a 10-s trial began. A vertical thin red line ran from left to right. Subjects initiated force production in a self-paced fashion (usually within the first 3 seconds) and were

encouraged to maintain isometric force production to match the red line as best as they could till the end of a trial. Four repetitions were recorded. Prior to the experiments, ten to fifteen practice trials were allowed during a familiarization session. Tasks (combinations of force level and breathing condition) were randomized. All subjects were given at least a 20-s interval between two consecutive trials in an attempt to minimize the effects of fatigue.

The force sensors were mounted inside a steel frame (140 mm × 90 mm each). The sensors were medio-laterally distributed 30 mm apart within the frame and adjustable in the forward-backward direction within the range of 60 mm. The steel frame with the sensors was placed between two horizontal aluminium bars that allowed horizontal adjustment of the frame. Such apparatus could accommodate individual subject's anatomy. Only one sensor was activated to measure the index finger force. Analog output signals from the sensor (208C02; PCB Piezotronics, Depew, NY) were connected to a separate signal conditioner (model 484B11, PCB Piezotronics Inc.). The force sensor had a range of 444.8 N. The resolution of the system was 2.715 mN/bit. The system involved approximately 1% error over the typical epoch of recording of a constant signal. Airflow and force signals were sampled at 1000 Hz by a 16-bit analog-to-digital converter (PCI-6229; National Instruments, Austin, TX) using a customized LabView software (National Instruments, Austin, TX). All signals were recorded for offline analysis using a customized Matlab program (The MathWorks, Natick, MA).

In order to assess the motor performance as a function of force and breathing, the mean force (F), standard deviation (S.D.) and coefficient of variation (CV) of the force data was computed. To standardize data analysis, F, S.D. and CV were calculated from the 5th to 7th second of the force data during normal breathing and the Valsalva maneuver. During forced inspiration and expiration, the moment when airflow crossed the axis prior to its peak (asterisk in Fig 1) was marked as the initiation point. F, S.D. and CV were computed from a 2-s window starting from the initiation point. F, S.D. and CV were averaged over 4 repetitions for each force and breathing condition.

Cross correlation between the ventilation data and force fluctuations was further analyzed for each breathing condition. For forced inspiration and expiration, correlation coefficients (CORR) were computed for the time window from the moment when airflow crossed the axis (t_{zero}) prior to its peak to the moment when airflow reached the peak (t_{peak}). For normal breathing, CORR were computed from t_{zero} to t_{peak} when t_{peak} was located between the 5th and 7th seconds. For the Valsalva maneuver, CORR were computed from the 5th to 6th seconds (there was approximately about 1 second from t_{zero} to t_{peak} for other breathing conditions). The absolute values of CORR were then averaged across force levels and repetitions for each breathing condition. Based on airflow signals, subject's performance during each task was confirmed by visual inspection.

Repeated measures two-way ANOVAs were used to detect any significant difference in F, S.D. and CV among force levels and breathing conditions. Factors were FORCE (3 levels, 15%, 30% 45%MVC) and BREATH (4 levels: normal breathing, forced inspiration, forced expiration, and the Valsalva maneuver). One-way ANOVAs were used to assess cross-correlations between ventilation and force fluctuations under different breathing conditions. The factor was BREATH. When significant interactions were obtained, the locations of the differences were determined using a *Tukey's* post hoc test. The alpha level for the statistical test was $P \leq 0.05$.

Figure 1 illustrates typical patterns of force and airflow during normal breathing vs. forced inspiration at 30%MVC. Airflow rate typically increased 2 to 3 folds during a forced ventilation. The index finger force coincidentally diverged from the static force output with the initiation of force inspiration. Correlation coefficients (CORR) between the ventilation data

and force fluctuations were significantly greater during force inspiration and expiration than during normal breathing and the Valsalva maneuver ($F_{[3,39]}=111.98$, $p<0.001$). On average, CORR for normal breathing, forced inspiration, forced expiration, and the Valsalva maneuver were 0.48 ± 0.09 (mean $\pm$ SD, range: 0.39~0.66), 0.74 ± 0.12 (range: 0.62~0.93), 0.74 ± 0.06 (range: 0.69~0.83), and 0.23 ± 0.06 (range: 0.10~0.34), respectively.

The mean force during actual force production was not significantly different across breathing conditions at each target level. The influence of ventilation on force variability (S.D.) was evident (Fig 2A). On average, S.D. increased with the level of force. At each force level, S.D. increased from normal breathing to forced inspiration and expiration about two-fold or more, while slightly decreased during the Valsalva maneuver (Fig 2A). A two-way ANOVA revealed main effects of BREATH ($F_{[3, 39]}=52.86$, $P < 0.001$) and FORCE ($F_{[2, 26]}=50.66$, $P < 0.001$), and a significant interaction of BREATH $\times$ FORCE ($F_{[6, 78]}=9.32$, $P < 0.001$). Post hoc analysis found that S.D. during forced expiration and inspiration was significantly greater than S.D. during normal breathing and the Valsalva maneuver at all levels of force. No significant difference in S.D. was found between forced expiration and forced inspiration or between normal breathing and the Valsalva maneuver.

Coefficient of variation (CV) of corresponding force data showed a similar pattern of results as S.D. (Fig 2B). Forced ventilation had impact on CV. A two-way ANOVA revealed main effects of BREATH ($F_{[3,39]}=77.98$, $p<0.001$), FORCE ($F_{[2,26]}=16.48$, $p<0.001$) and a significant interaction of BREATH $\times$ FORCE ($F_{[6,78]}=4.66$, $p<0.001$). According to post-hoc tests, CV during forced expiration and inspiration was significantly greater than CV during normal breathing and the Valsalva maneuver at all levels of force. No significant difference in CV was found between forced expiration and forced inspiration or between normal breathing and the Valsalva maneuver.

In the present study, we replicated the well-documented observation [6,9,19,20] that force variability increased with the level of force during the moderate range (15% to 45% MVC). This study also demonstrated clearly that, with no significant change in the mean force at each target level, force variability was significantly greater during forced inspiration and expiration, but not during the Valsalva maneuver, as compared to normal breathing. Furthermore, force fluctuations were coincident with the initiation of force ventilation. These novel findings tentatively supported our hypothesis that forced inspiration and expiration increased force variability. Our finding was similar to an earlier study that breathing altered the precision of visually-guided finger tracking movements [18]. Because the mean force of actual force production at each force level was the same for each breathing condition, the neurophysiological mechanisms proposed to explain the linearity between force variability and force level, such as unfused firing of motor units, discharge rate variability or both, were not likely to play a critical role for the increases in force variability during forced ventilation at submaximal levels.

Forced inspiration and expiration has been reported to be synchronized with transient enhancement in respiratory-related neuronal activity at numerous cortical sites, including the primary motor cortex [8,10,16]. These enhanced cortical activities are likely to act in concert with the descending motor drive to the exercising, non-respiratory muscles [12], such as the finger flexors. In the earlier study [14], forced expiration was synchronized with an initial force peak. This peak was attributed to the respiratory-motor enhancement mechanism associated with transient increases in respiratory-related neuronal activity. In the study, the cross correlation analysis provided evidence that the initiation of forced ventilation correlated well force fluctuations at submaximal levels (cf. Fig 1). The observation of significant increase in force variability synchronized with forced ventilation further supported the proposed mechanism of respiratory-motor enhancement [14] at submaximal force levels.

For static force output to occur, the involved joints need to be stabilized during continuous force production. Any disturbance in relative levels of activations in the agonists or antagonists would lead to fluctuations in force output. Li and Laskin [14] showed that, during finger flexion MVC attempts, the flexor/extensor ratio [flexor digitorum superficialis (FDS)/extensor digitorum communis (EDC)] in electromyographic (EMG) activities increased significantly during both forced inspiration and expiration; while the FDS/EDC ratio was not changed during the Valsalva maneuver. The increased FDS/EDC ratio was found to be coincident with the initial force peak during MVC attempts [14]. Therefore, increases in FDS/EDC ratio by forced inspiration and expiration could transiently interfere with joint stability during continuous isometric force production at submaximal levels, resulting in greater force variability. On the other hand, maintenance of FDS/EDC ratio during the Valsalva maneuver, as found in MVC attempts [14], suggests that stability of the involved joints is not likely to be disturbed, thus no change in force variability is observed (Fig 2). This interpretation could be corroborated by the observed synchronization of the initiation of forced ventilation with increased force variability, while no such synchronization was found between the ventilation data and force fluctuations during the Valsalva maneuver.

Variability of motor performance usually increases during dual tasks that require attention allocation to different task components [1,2,25]. Initiation of self-paced forced respiration or of the Valsalva maneuver while maintaining static force output (rely on visual feedback) may be viewed as a dual task, resulting in observed greater force variability. Both force inspiration and expiration are rhythmical tasks, whereas the Valsalva maneuver is a static task that requires significantly less cognitive processing. Furthermore, voluntary inhibition of respiratory activities during the Valsalva maneuver requires attention allocation. It is possible that increased force variability during forced ventilation could be partly attributable to “dual tasking”. Visual information may play an important role in maintaining static force output, particularly during forced ventilation. For instance, visual feedback could help correct subsequent force fluctuations after the initial force divergence that is synchronized with the initiation of forced ventilation, i.e., to maintain static force output; while it requires attention, serving as a source of “dual tasking”. It is not likely, however, that visual information imposes significant impact on force variability during different breathing conditions.

In conclusion, the present study demonstrated clearly that force variability increased with force level, and that force variability increased during forced ventilation, but not the Valsalva maneuver, as compared to normal breathing. Increased force variability was coincident with the initiation of forced ventilation. Therefore, assessment of force variability should consider the influence of breathing.

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Figure 1.

Representative trials recorded from the same subject during normal breathing (solid line) and forced inspiration at 30% MVC. Force deviation was coincident with the initiation of forced inspiration. Positive airflow: inspiration; negative airflow: expiration. Asterisk: peak of forced inspiration.

Figure 2.

The influence of ventilation of standard deviation (S.D., A) and coefficient of variation (CV, B) of isometric finger force production. S.D. and CV were greater during forced inspiration (In) and expiration (Out), but not the Valsalva maneuver (Val), as compared to normal breathing (Normal). S.D. increased with force level, while CV did not change with the force level. Mean ($n=14$) and standard error bars are presented.