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Effect of an inverted seated position with upper arm blood flow restriction on measures of elbow flexors neuromuscular performance

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Abstract

Purpose

The objective of the investigation was to determine the concomitant effects of upper arm blood flow restriction (BFR) and inversion on elbow flexors neuromuscular responses.

Methods

Randomly allocated, 13 volunteers performed four conditions in a within-subject design: rest (control, 1-min upright position without BFR), control (1-min upright with BFR), 1-min inverted (without BFR), and 1-min inverted with BFR. Evoked and voluntary contractile properties, before, during and after a 30-s maximum voluntary contraction (MVC) exercise intervention were examined as well as pain scale.

Results

Inversion induced significant pre-exercise intervention decreases in elbow flexors MVC (21.1%, $\eta_p^2 = 0.48$, $p = 0.02$) and resting evoked twitch forces (29.4%, $\eta_p^2 = 0.34$, $p = 0.03$). The 30-s MVC induced significantly greater pre- to post-test decreases in potentiated twitch force ($\eta_p^2 = 0.61$, $p = 0.0009$) during inversion (↓75%) than upright (↓65.3%) conditions. Overall, BFR decreased MVC force 4.8% ($\eta_p^2 = 0.37$, $p = 0.05$). For upright position, BFR induced 21.0% reductions in M-wave amplitude ($\eta_p^2 = 0.44$, $p = 0.04$). There were no significant differences for electromyographic activity or voluntary activation as measured with the interpolated twitch technique. For all conditions, there was a significant increase in pain scale between the 40–60 s intervals and post-30-s MVC (upright<inversion, and without BFR<BFR).

Conclusion

The concomitant application of inversion with elbow flexors BFR only amplified neuromuscular performance impairments to a small degree. Individuals who execute forceful contractions when inverted or with BFR should be cognizant that force output may be impaired.

Introduction

Individuals can experience an involuntary inverted posture such as with an overturned vehicle or voluntary inversion with aerial maneuvers and sports (e.g. gymnastics). A decrease in force or power output, with an increased perceived difficulty in some situations can be life threatening or affect performance. For example, in an overturned vehicle (e.g. car, helicopter) the victim must have sufficient force to release the seat belt and shoulder harness while constrained by their body mass and blood flow can be restricted by both the harness and near maximal muscle contractions. Although inhibited neuromuscular function (i.e., force, rate of force development) has been reported when shifting from an upright to an inverted position [1–5], the underlying mechanisms are not clearly elucidated. Altered sympathetic nervous system activity during inversion (i.e., higher hydrostatic pressure increases vagal inputs), has been suggested as one primary mechanism that may influence changes in neuromuscular functions with inversion [1–4]. Inversion-induced hydrostatic pressure has also been suggested to contribute to neuromuscular impairments in animals [6–9] and humans [10].

Changes in perfusion pressure to a target muscle can be found during contractions at moderate-to-high intensities [11], low-intensity contractions combined with blood flow restriction (BFR) [12], and when the position of a working muscle changes in respect to the level of heart (i.e., above the heart induced lower perfusion pressure) [13]. Decrements in neural function and perceived exertion can be exacerbated by changes in perfusion pressure and reduced oxygen-induced peripheral fatigue [14], which for example can occur if an individual is trapped in a position with load exerted upon an immobilized limb. A squeezed or compressed limb can lead to ischaemia, increasing metabolic by-product accumulation, thereby activating pain afferents (group III and IV) [15–17], contributing to central nervous system inhibition [15]. Decreased force production and muscle performance were observed with changes in perfusion pressure (i.e. an arm lifted above the heart level) [18] and graded ischaemia of the lower limb [10]. Hobbs and McCloskey [19] indicated that with ischemia, there was greater muscle activity (electromyography: EMG) to keep the force output at the requisite level. Partial occlusion (increased pressure and ischaemia) concomitant with prolonged exercise could influence the perception of effort and sense of pain [20]. Although both inversion [1–4] and blood flow restriction [10,14,18,19] can alter force output and muscle activation, the combination of inversion (increased hydrostatic pressure) with blood flow restriction (BFR: increased perfusion pressure), on neuromuscular performance has not been previously investigated. It is unknown whether additive effects of hydrostatic (whole body effects) and perfusion (local muscle effects) pressure occur (inversion and BFR respectively), exacerbating neuromuscular performance decrements.

With these contexts, the objective of this study was to investigate the potential effects of a one-minute inverted position with upper arm BFR on measures of elbow flexors isometric maximum voluntary contraction (MVC) force production, biceps and triceps brachii electromyographic (EMG) activity, perceived pain, and performance fatiguability (extent of force reduction with a 30-s MVC). Based on prior inversion studies [1–4], it was hypothesized, that inversion and BFR would decrease both voluntary and evoked force output, decrease voluntary activation, and increase fatigue during the 30-s MVC, and the addition of BFR to inversion would amplify these impairments to neuromuscular function.

Materials and methods

Participants

Based on the force data from previous studies on similar research topics [1,2], a statistical a priori power analysis (G*Power 3.1, Dusseldorf, Germany) indicated that a minimum of six participants would be needed to attain an alpha of 0.05 (α error) with an actual power of 0.8 (1-β error). We were able to recruit a convenience sample of 13 (males, n = 7, age: 24.7 ± 4.9, height: 178.3 ± 8.3 cm, and mass: 79.9 ± 8.6 kg and females, n = 6, age: 24.5 ± 4.8, height: 162.0 ± 3.6 cm, and mass: 73.5 ± 14.3 kg) healthy physically active university students. Participants performed structured physical activity 3–4 days per week, which included resistance training on a regular (1–3 times per week) basis for the prior six months. They had no previous history of cerebral, hypertensive, or visual health problems or injuries. The participants were given an overview of all procedures (i.e., orientation and testing sessions) before data collection. If willing to participate, participants signed the consent form and completed a 'Physical Activity Readiness Questionnaire for Everyone' (PAR-Q+: Canadian Society for Exercise Physiology, approved September 12, 2011 version). The Interdisciplinary Committee on Ethics in Human Research, Memorial University of Newfoundland (ICEHR Approval #: 20192154-HK) approved this study and the study was conducted in accordance with the latest version of the Declaration of Helsinki.

Experimental design

Based on the recommendation of the Canadian Society for Exercise Physiology [21], participants were advised to not smoke, drink alcohol or partake in intensive physical activity six hours prior to testing and to not eat food or ingest caffeine two hours before participating in the testing procedure. Participants attended an orientation session, at least a week before data collection, where they were familiarized with both upright and inversion postures; and also became familiar with BFR, the interpolated twitch technique (ITT), EMG electrode placement, and isometric maximal voluntary contractions (MVC) techniques. Following the orientation session, all participants were capable of achieving near maximal (83.5%-95.9%) voluntary activation before commencing the experimental conditions. Using random allocation (generated by Microsoft Excel) participants performed four, ~60 minutes, experimental conditions in a within subject design: 1) Control (1-min upright position without BFR), 2) Control with BFR (1-min upright position with BFR), 3) 1-min inversion (without BFR), and 4) Combined: 1-min inversion with BFR. Testing included 1) initial testing (upright seated position pre-fatigue), 2) pre-testing (one of the four conditions pre-fatigue) and post-testing after the 30-s MVC (one of the four conditions after the 30-s MVC). There was approximately 48 h between each experimental condition. To decrease diurnal rhythms effects, all of the test procedures were completed at approximately the same time of day. The temperature of the laboratory was maintained at 20C.

Maximal evoked muscle twitch (i.e., resting position) and voluntary contractile properties (MVC with ITT) were initially tested from an upright seated position. The participant then performed a warm-up, which consisted of arm cycling (cycle ergometer: Monark Ltd. Sweden), at 70 rpm with 1 kp for 5-min; followed by a specific warm-up of five 5-s isometric elbow flexion (~50% of perceived maximum) contractions. Following the warm-up and a 5-min rest period, pre-fatigue BFR testing procedures (relative to the posture) with the participant positioned in the inversion chair were assessed. The subsequent condition/position (without/with an upper right arm BFR) also included an evoked twitch (10-s after achieving desired position or condition), MVC with ITT (5-s after the evoked twitch), a 30-s MVC protocol (5-s after

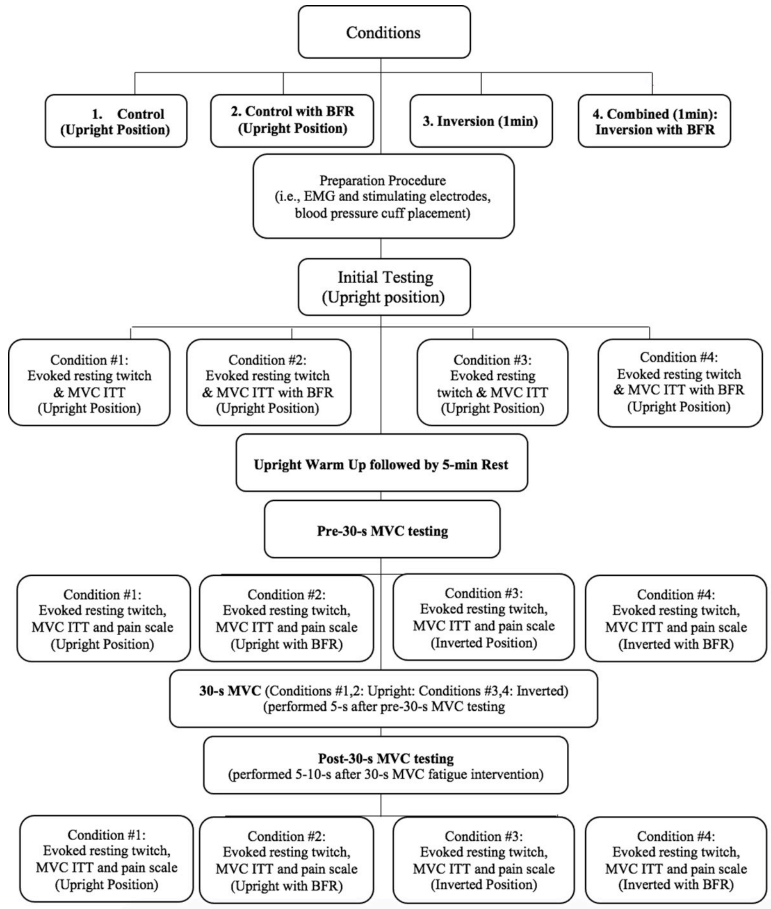

Fig 1. Experimental design.

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MVC), followed by another evoked twitch and MVC with ITT (5- and 10-s after 30-s MVC respectively) (Fig 1). It is noted that there was a 5-s transition from both upright to supine, and supine to inversion positions. In total, a participant was placed at each condition for 150s, from positioning at the desired posture to post-30s MVC measures (i.e., post-fatigue evoked twitch, MVC ITT, and potentiated twitch force).

Force measures

For voluntary and evoked force measures, the participants were seated in an inversion chair (initially in an upright position), which was designed and constructed by Technical Services of Memorial University of Newfoundland [1,3,4]. The chair can rotate through a 360-degree range. Straps secured the participant at the head, torso, shoulder, hip, and thighs. Hips and knees were positioned at 90^0 during data collection. A Wheatstone bridge configuration strain gauge (Omega Engineering Inc., Don Mills, Ont.) via a high-tension wire cable was attached to a reinforced strap around the right wrist to assess force output, and forces were collected and amplified via analog to digital data collection hardware and software (i.e., Biopac System Inc. DA 100, A/D convertor MP100WSW; Holliston, MA). Due to the physical layout of the laboratory equipment, the right elbow flexors were tested.

Evoked contractile properties

To assess evoked twitch forces and muscle compound action potentials (M-wave), evoked contractile properties were measured. To stimulate the musculocutaneous nerve, stimulating electrodes (electrode width was 5 cm) were placed at the intersection of the biceps brachii and deltoid (anode) and antecubital space (cathode), respectively [22]. Furthermore, the placement of electrodes was marked with ink from test to test to maintain the correct position of electrodes during each session. Stimulating electrodes were connected to a stimulator (Digitimer Stimulator, Model DS7AH, Hertfordshire, UK) with a maximum of one ampere (A) and 400 volts (V). Then, both amperage (10 mA– 1 A) and voltage (100–400 V) of the 200-μs duration square wave pulse were increased sequentially by 10mA increments until a plateau in the twitch torque and M-wave was attained. The electrode leads were taped to the participants' arm to reduce movement and stress on the lines.

While the initial resting twitch involved a single stimulus, the superimposed and subsequent potentiated twitches had a 10 ms inter-pulse interval between two maximal twitches during biceps brachii nerve stimulation [23]. The ITT using doublet stimulation has been reported to be a valid and reliable measure of voluntary muscle activation (VMA) [23].

Previous studies [23–26] have shown that there is a possibility to activate all muscle fibres via a superimposed twitch on a voluntary contraction (ITT). For consistency, each session commenced with an initial evoked twitch. Since evoked single twitches are sensitive to prior contractions resulting in a potentiated response, the twitches were evoked both prior to (resting twitch) and after (potentiated twitch) the MVC testing [27,28]. Superimposed twitches were delivered during 2–3 MVCs (4-s duration with 2-min rest between each MVC), before the BFR and fatigue intervention, and once following the BFR and 30-s MVC fatiguing muscle contraction (i.e., MVC during elbow flexion). The first supramaximal (120% of maximum) electrical stimulation was delivered at the 3-s point of the MVC (all participants could achieve maximal force within this duration), and the second twitch (as a potentiated twitch) was evoked at a 3-s interval after the MVC (subject was instructed to relax). This procedure was repeated if the MVC force of the second MVC was 5% higher than the first MVC [1,22–25,28,29]. To estimate VMA, the amplitudes of the superimposed and post-contraction stimulation were compared [voluntary activation = [1 –(superimposed twitch/potentiated twitch)] * 100] [23].

A fatiguing protocol consisting of a 30-s MVC of the elbow flexors, was performed using an isometric elbow flexion MVC (right arm). The researcher provided consistent verbal encouragement in terms of wording and timing (e.g., "keep it up" every 10 s, starting at 10 s point).

Voluntary contractile properties

With the same set-up as the evoked contractile properties, elbow flexors MVC isometric force was measured while seated and secured in the inversion chair with a supinated forearm at a 90° elbow flexion angle with shoulders at 0° (mid-frontal plane), with a reinforced strap around the right wrist. An instruction ("as hard and as fast as possible"), with verbal encouragement ("go go") was provided by the researcher during the entire 4-s isometric MVC. The forces detected by the strain gauge, were used to analyze the peak isometric MVC.

Electromyography (EMG)

Surface EMG was monitored during evoked twitches (muscle action potential: M-wave), 4-s MVC and 30-s MVC. First, the skin was prepared before electrode placement with shaving (removal hair), abrading (to remove possible dead epithelial cells), and cleaning the area with an alcohol swab to remove oils. Then, two pairs of bipolar electrodes (Kendall Medi-trace 100 series, Chikopee, Mass.) were positioned (established by SENIAM) [30] at the mid-belly of the biceps brachii (i.e., at 50% on the line from medial acromion to the fossa cubit) as an agonist muscle (corresponding to the muscle fibres), and the lateral head of the triceps brachii (i.e., halfway from the posterior crista of the acromion to the olecranon as an antagonist muscle). Bipolar electrodes were placed collar to collar (2 cm apart).The reference electrode was positioned on the ulnar styloid process.

The EMG signal was collected at 2000 Hz, band-pass filter 10–500 Hz and amplified 1000x (Biopac System MEC 100 amplifier, Santa Barbara, Calif; input impedance = 2M, common mode rejection ratio > 100 dB minimum [50/60 Hz]). The collected data (via the A/D converter, Biopac MP150) was stored on a personal computer for post-processing analysis. The final data (i.e., raw EMG) was rectified and integrated over 500 ms following an MVC [2–4].

Blood flow restriction (BFR)

To decrease potential harmful biological effects, which can occur following an extremely high dose of BFR [31], previous evidence [32] using Doppler ultrasonograms showed that a moderate BFR and partial occlusion of the brachial artery can lead to 100% venous restriction and partial arterial BFR, respectively. In order to reduce hydrostatic pressure effects, and perfusion to the right elbow flexors muscles, BFR was implemented. At the resting position, a pressure cuff (A+ Med 7–62 pressure cuff; Toronto, Canada) was placed around the upper right arm, while positioned at the level of the heart. Then, the hand bulb was squeezed to manually find a pulse elimination pressure (100% BFR). The individualized BFR in the present study was set relative to brachial systolic blood pressure. To create partial BFR for upright/inverted position, the hand bulb was squeezed to 50% of complete BFR. Furthermore, with a maximal isometric contraction, the blood flow would be further restricted, obviating the need for maximal BFR with a cuff.

Universal pain assessment tool

The researcher utilized a universal pain assessment tool (scale with numbers and cartoon facial Figs) [33] to assess the degree of overall discomfort (pain perception) during inversion. Also, to investigate whether there was any interaction between the effects of inversion and BFR (during two control sessions), the sense of discomfort with and without BFR was examined.

Data analysis

All data analyses were conducted using the AcqKnowledge software program (Biopac System Inc. Holliston, MA). With the single electrical stimulation, peak twitch force (Newtons), time to peak twitch force (ms), half relaxation time (ms) and M wave (millivolts: mV) were measured for resting and potentiated twitches. Peak MVC forces [34] were analyzed. The resting force output in the upright position was zeroed and used as the baseline when compensating for the suspended arm mass in the inverted position. The mass of the arm was recorded in the inverted position and this value subtracted from the peak force in order to counterbalance the force of gravity negatively affecting force output in the upright position. A force fatigue index was calculated from the 30-s MVC, which involved dividing the mean force of the last 5-seconds of the fatigue protocol into the mean force output of the first 5-seconds.

The peak amplitude of integrated EMGs, from the biceps and triceps brachii, were analyzed from a one second period of the 4-s MVC (before the superimposed twitch) [29]. Furthermore, a Fast Fourier transform was used to report the EMG median frequency following the fatigue protocol, as it is a reliable indicator for signal conduction velocity (following a fatiguedexercise) and generally considered a more sensitive indicator of fatigue than a raw EMG signal [35–38].

Statistical analysis

The SPSS software (version 23.0, SPSS, Inc. Chicago, IL) was used for statistical analysis. Normality of the data was assessed and confirmed using a histogram chart to illustrate skewness and kurtosis with a Shapiro-Wilks test. The value of Greenhouse-Geisser were reported if the assumption of sphericity was not met. Initially, sex effects were considered as a factor, but with a lack of any significant differences, the sample population was integrated for analysis. To determine the effect of inversion with BFR on fatigue index of the 30-s MVC, a two-way repeated measures ANOVA (2 seated positions × 2 blood flow conditions), while three-way repeated measures ANOVA (2 seated positions × 2 blood flow conditions × 2 times) was conducted for EMG median frequency. For the evoked twitches, MVCs, ITT, potentiation twitches, muscle action potential (M-) waves, EMG, a three-way ANOVA (2 seated positions and 2 blood flow conditions and three times [initial upright resting position, pre-, and post-30-s MVC]) was applied. Further, a repeated measures ANOVA was conducted to analyze the pain scale. Differences were considered significant when a minimum value of $p = 0.05$ was reached. Planned pairwise comparisons; Bonferroni adjustment, was selected to compare main effects. Additionally, the calculated partial eta squared (η_p^2) by SPSS was reported as a magnitude of outcomes (effect sizes); which is classified as small ($0.00 \leq \eta_p^2 \leq 0.24$), medium ($0.25 \leq \eta_p^2 \leq 0.39$), and large ($\eta_p^2 \geq 0.40$) [39]. Day to day reliability of measures (for initial upright resting position test) was assessed with Cronbach's alpha intraclass correlation coefficient (ICC).

Results

Within the results text and Figs, significant interactions are reported. Main effects are listed and described in Table 1. All data is available from the Open Science Framework: DOI 10.17605/OSF.IO/TZM4B. Representative raw data sample tracings are provided in Fig 2.

Reliability

With the exception of moderate internal consistency (0.7) for biceps brachii's M-wave, and acceptable ($0.7 \leq \alpha < 0.8$) reliability for resting twitch force, ICC reliability scores were excellent ($0.82 \leq \alpha < 0.94$) for MVC forces, potentiated twitch forces, biceps and triceps brachii EMG (Table 2).

Voluntary contractile properties

Elbow flexors MVC. A significant seated position x time interaction ($F_{(2,16)} = 5.07$, $p = 0.02$, ($\eta_p^2 = 0.48$) (Fig 3) was observed for elbow flexor MVC force. The interaction revealed 9.1% and 21.1% MVC force decrements with the initial measures exceeding pre-fatigue measures for upright and inverted positions, respectively. Furthermore, there were 21.4% and 14.2% force impairments from the initial and pre-test to post-test respectively for the upright position. Similarly, there were 33.1% and 17.7% decrements from the initial and pre-test to post-test respectively for the inverted position. A non-significant, medium effect size, seated position x BFR interaction ($F_{(1,8)} = 3.79$, $p = 0.08$, $\eta_p^2 = 0.32$); demonstrated 9.1% lower MVC forces with BFR compared to without BFR for inverted seated positions.

Table 1. Main effects (means ± standard deviation).

Main Effects for Time	**Initial Test**	**Pre-Fatigue**	**Post-Fatigue**	**Initial to Pre-Fatigue**	**Pre to Post-Fatigue**
MVC Force (N) $F_{(2,16)} = 52.58$	309.32 ± 84.55	269.18 ± 75.16	226.30 ± 63.38	$p<0.001$, $\eta_p^2 = 0.82$, Δ14.9%	$p<0.001$, $\eta_p^2 = 0.84$ Δ18.9%
F100 (N) ($F_{(2,18)} = 31.81$	73.28 ± 36.47	52.14 ± 25.64	34.32 ± 18.17	$p = 0.003$, $\eta_p^2 = 0.63$ Δ40.5%	$p<0.001$, $\eta_p^2 = 0.80$ Δ51.9%
BB EMG (mV/s) $F_{(1,12)} = 22.41$	0.30 ± 0.16	0.29 ± 0.15	0.24 ± 0.12	$p>0.05$	$p<0.001$, $\eta_p^2 = 0.65$ Δ22.0%
TB EMG (mV/s) $F_{(1,8)} = 7.34$	0.07 ± 0.02	0.06 ± 0.02	0.05 ± 0.01	$p = 0.02$, $\eta_p^2 = 0.47$ Δ16.6%	$p = 0.003$, $\eta_p^2 = 0.67$ Δ20.0%
BB M-wave (mV) $F_{(1,7)} = 3.89$	9.05 ± 4.06	8.96 ± 3.22	8.49 ± 2.95	*p>0.05*	$p = 0.08$, $\eta_p^2 = 0.35$ Δ7.6%
PTF (N) $F_{(2,10)} = 36.3$	66.48 ± 19.11	63.82 ± 18.38	28.86 ± 14.07	$p>0.05$	$p<0.001$, $\eta_p^2 = 0.87$ Δ121.1%
VMA (%) $F_{(1,4)} = 6.62$	91.71 ± 5.36	92.47 ± 3.44	82.53 ± 11.35	$p>0.05$	$p = 0.06$, $\eta_p^2 = 0.62$ Δ12.0%
Main Effects for BFR	**no BFR Conditions**		**BFR Conditions**	**no-BFR to BFR**	
MVC Force (N) $F_{(1,8)} = 4.84$	274.61 ± 76.60		261.93 ± 72.12	$p = 0.05$, $\eta_p^2 = 0.37$ Δ4.8%	
BB M-Wave (mV) $F_{(1,7)} = 7.28$	9.67 ± 2.11		7.99 ± 2.44	$P = 0.03$, $\eta_p^2 = 0.51$ Δ21.0%	
Perceived Pain Scale $F_{(1,12)} = 7.85$,	2.5 ± 2.59		3.19 ± 2.27	$p = 0.01$, $\eta_p^2 = 0.39$ 15.6%	
Main Effects for Seated Position	**Upright Seated Positions**		**Inverted Seated Positions**	**Upright *vs*. Inverted**	
F100 (N) $F_{(1,9)} = 3.42$	58.27 ± 28.01		48.22 ± 25.51	$p = 0.09$, $\eta_p^2 = 0.27$ Δ8.3%	
Perceived Pain Scale $F_{(1,12)} = 14.56$,	2.26 ± 1.98		3.42 ± 2.8	$p = 0.002$, $\eta_p^2 = 0.54$ Δ26.5%	
Main Time Effects for Fatigue–Force, and Fatigue -EMG Relationships	**0-5s interval (no-BFR and BFR)**		**25-30s interval (no-BFR and BFR)**	**0-5s to 25-30s intervals**	
Force (N) $F_{(1,11)} = 29.96$	278.42 ± 85.72		242.86 ± 74.45	$p<0.001$, $\eta_p^2 = 0.73$ Δ14.6%	
BB EMG Median Frequency (Hz) $F_{(1,10)} = 84.65$	57.67 ± 10.61		41.32 ± 5.59	$p<0.001$, $\eta_p^2 = 0.89$ Δ39.5%	
TB EMG Median Frequency (Hz) $F_{(1,12)} = 86.69$	59.25 ± 12.53		44.26 ± 9.25	$p<0.001$, $\eta_p^2 = 0.87$ Δ33.8%	

*BB = Biceps Brachii, EMG: Electromyography, F100: Force output within the first 100 ms of the MVC, MVC: Isometric maximal voluntary contraction, M-wave: Muscle action potential, PTF = Potentiated Twitch Force, RTF = Resting Twitch Force, TB = Triceps Brachii, VMA = Voluntary Muscle Activation.

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Voluntary muscle activation (VMA %). A non-significant, but large eta^2 magnitude, BFR x time interaction revealed 7.9% and 16.4% decrements post-30-s MVC ($F_{(1,4)} = 5.48$, $p = 0.07$, $\eta_p^2 = 0.57$) for without BFR and BFR conditions, respectively (Fig 4).

Evoked twitch contractile properties. A significant seated position x time interaction ($F_{(1,11)} = 5.80$, $p = 0.03$, $\eta_p^2 = 0.34$), for resting pre-MVC twitch force revealed that initial values exceeded pre-30-s MVC, by 29.4% for inverted seated positions (Fig 5). No significant effects or interaction were found for baseline time to peak twitch force. Meanwhile, a non-significant, large magnitude effect size effect was observed ($F_{(1,6)} = 4.81$, $p = 0.07$, $\eta_p^2 = 0.44$), in terms of seated position and BFR, when comparing upright values (without BFR<BFR, 3.9%↑) with inverted seated positions (without BFR>BFR, 5.6%↓). No significant effects were observed for half relaxation time-twitch force.

Biceps and triceps brachii M-wave. A significant seated position x BFR interaction ($F_{(1,7)} = 5.69$, $p = 0.04$, $\eta_p^2 = 0.44$), revealed that the without BFR condition exceeded BFR condition biceps brachii's M-wave by 30.4% and 12.5% for upright, and inverted seated positions, respectively (Fig 6).

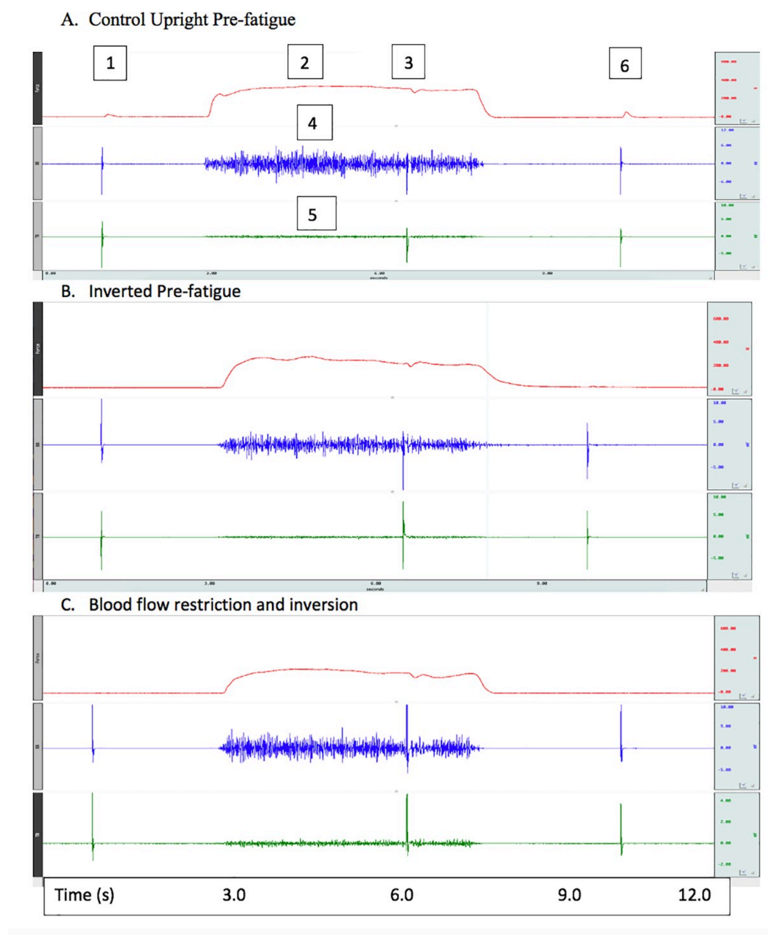

Fig 2. Representative 1) evoked resting twitch, 2) MVC force, 3) interpolated twitch technique (ITT), 4) biceps brachii EMG, 5) triceps brachii EMG and 6) potentiated twitch force (PTF) tracings presented under different conditions/posture. Top channel represents elbow flexor MVC force, second channel illustrates biceps brachii EMG and third channel shows triceps brachii EMG.

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Evoked potentiated twitch contractile properties. Significant seated position x time interaction ($F_{(2,10)} = 7.91$, $p = 0.009$, $\eta_p^2 = 0.61$) was observed for potentiated twitch force (PTF). The pre- and post-30-s MVC results showed 65.3% and 75% PTF impairments for upright and inverted positions from pre-to post 30-s MVC, respectively (Fig 7).

Fatigue–force relation. When comparing force output values, at 0–5 s and 25–30 s intervals of the 30-s MVC task in the without BFR conditions versus 0–5 s and 25–30 s of BFR conditions, there was 4.1% force decrements for BFR effects ($F_{(1,11)} = 5.54$, $p = 0.03$, $\eta_p^2 = 0.33$).

Table 2. Daily intraclass correlation coefficient reliability (initial resting position test performed on separate days).

	MVC	F100	BB EMG	TB EMG	RTF	BB M-wave	TB M-wave	PTF
ICC	0.93	0.82	0.94	0.83	0.77	0.66	0.6	0.87
CV	0.28	0.51	0.54	0.48	0.41	0.34	0.40	0.43
TEM	35.17	32.68	0.07	0.03	15.77	2.05	1.7	10.12

*BB = Biceps Brachii, CV: Coefficient of variance, EMG: Electromyography, F100: Force output within the first 100 ms of the MVC, MVC: Isometric maximal voluntary contraction, M-wave: Muscle action potential, PTF = Potentiated Twitch Force, RTF = Resting Twitch Force, TB = Triceps Brachii, TEM = typical error of measurement.

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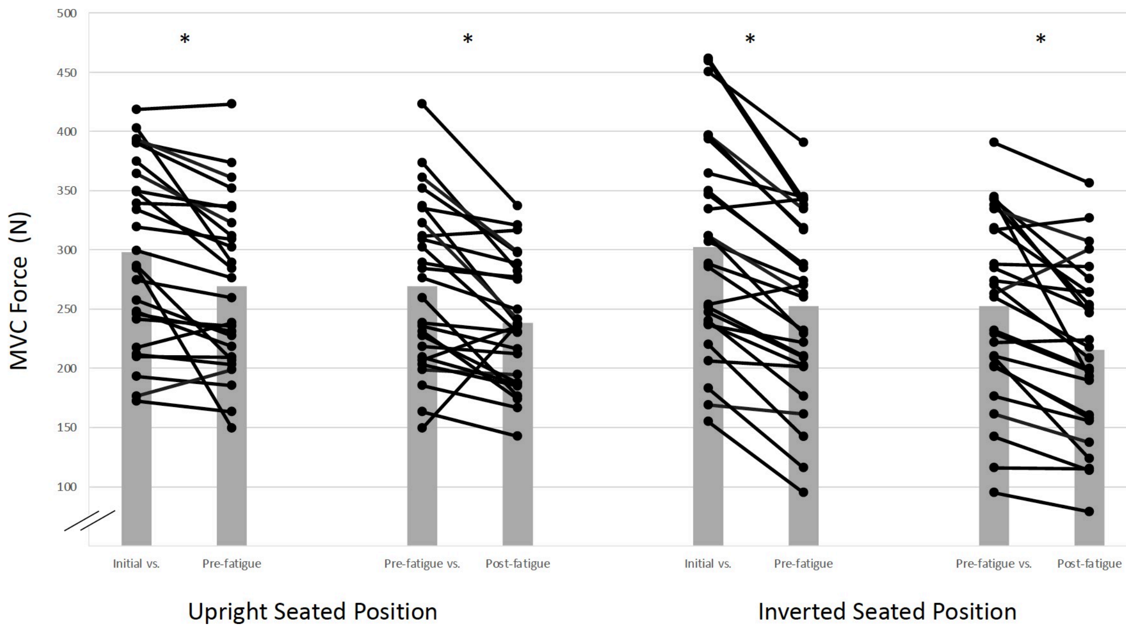

Fig 3. Isometric maximal voluntary contraction force (MVC) interaction effects for seated position and time. Star (*) symbol represents that significant MVC force decreases between initial and pre-fatigue tests, for upright and inverted seated positions. Means and standard deviations are illustrated. There was no statistically significant BFR interaction.

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Fatigue—EMG relation. *Biceps brachii*. Furthermore, contrasts revealed a non-significant, medium magnitude effect size, seated position x time interaction ($F_{(1,10)} = 3.84$, $p = 0.07$, $\eta_p^2 = 0.27$); with 45.6% and 38.6% decreases in biceps brachii EMG median frequency during upright without BFR and BFR conditions respectively, versus similar 32.8% and 41.4% median frequency decrements during the inverted seated position for without BFR and BFR conditions, respectively (Table 2).

Perceived pain—pain scale. Seated position x BFR interaction revealed significant differences ($F_{(1,12)} = 6.55$, $p = 0.02$, $\eta_p^2 = 0.35$) between upright (without BFR<BFR, 0.64 to 1.53, 58.1%↑) and inversion (without BFR>BFR, 2.70 to 2.43, -11.1%) positions. For the interaction of BFR x time

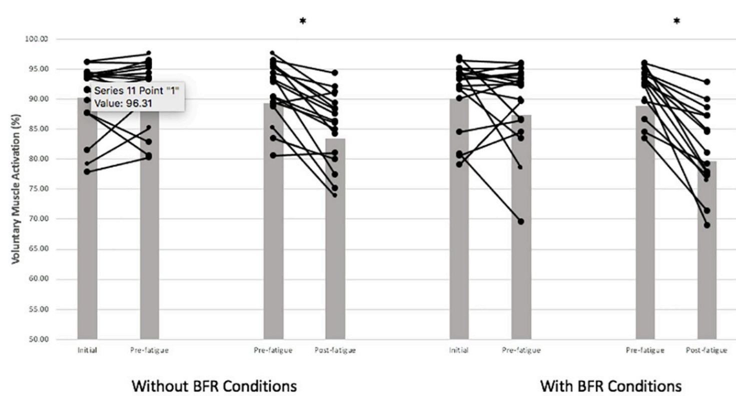

Fig 4. Voluntary muscle activation (VMA) interaction effects for BFR and time. There was a non-significant effect for percentage of VMA ($p = 0.07$), with 7.9% and 16.4% decreases post-fatigue for without BFR and BFR conditions. Means and standard deviations are illustrated. There was no statistically significant interaction between seated positions (inverted versus upright).

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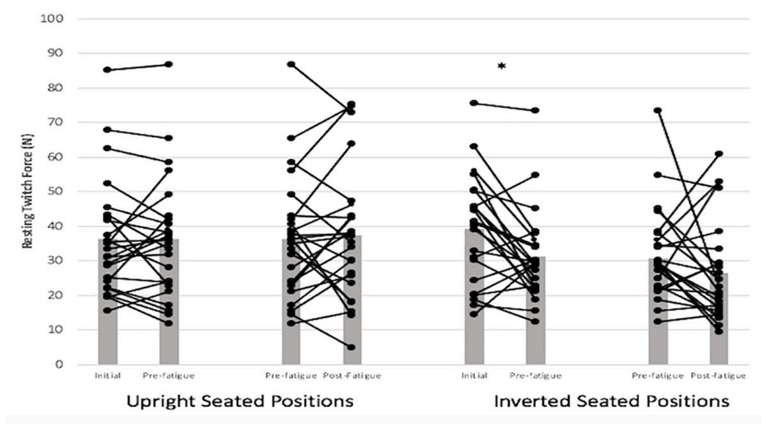

Fig 5. Resting twitch force interaction effects for seated position and time. Star (*) symbol represents significant decreases between initial and pre-fatigue tests, for upright and inverted seated positions. Means and standard deviations are illustrated. There was no statistically significant BFR interaction.

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($F_{(2.05,24.62)} = 4.68$, $p = 0.01$, $\eta_p^2 = 0.28$), a 4.6% pain scale decrease between 20–40 s and 40-60s intervals for the without BFR condition, contrasted with an overall (both without BFR and BFR) increase from initial (upright/inverted) to post-30-s MVC measures. Furthermore, a seated position x BFR x time interaction ($F_{(2.87,34.47)} = 3.18$, $p = 0.03$, $\eta_p^2 = 0.29$) showed significant differences when comparing without BFR and BFR, upright versus inverted conditions between 0–20 s and

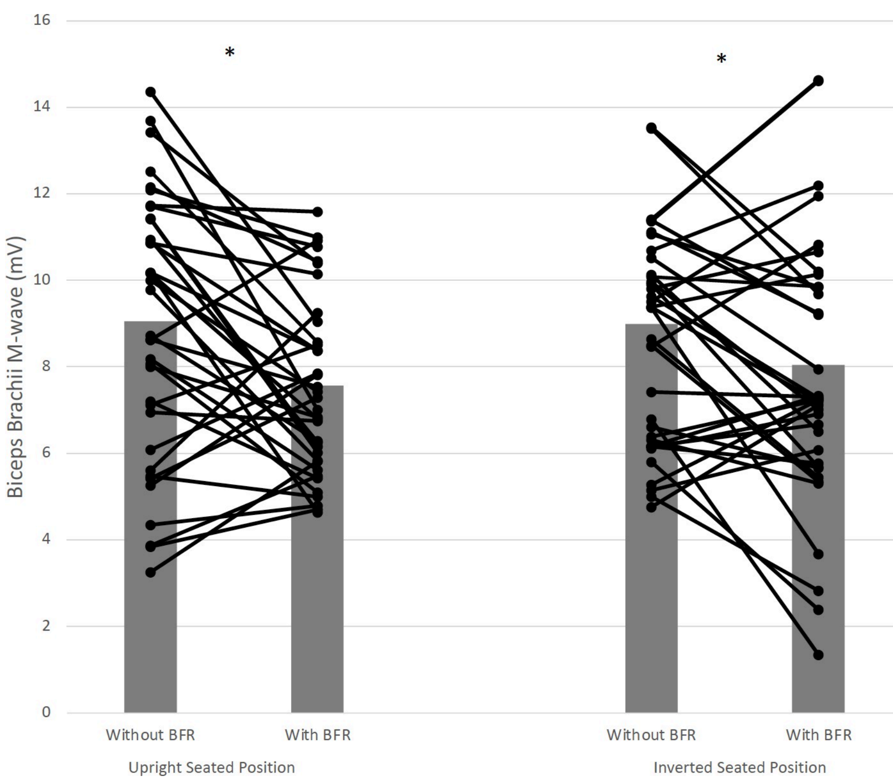

Fig 6. Biceps brachii M-wave interaction effects for seated position and BFR. Star (*) symbol represents that significant decreases in amplitude of M-wave for Biceps Brachii, between without BFR and BFR, with 30.4% and 12.5% for upright and inverted seated positions, respectively. Means and standard deviations are illustrated.

https://doi.org/10.1371/journal.pone.0245311.g006

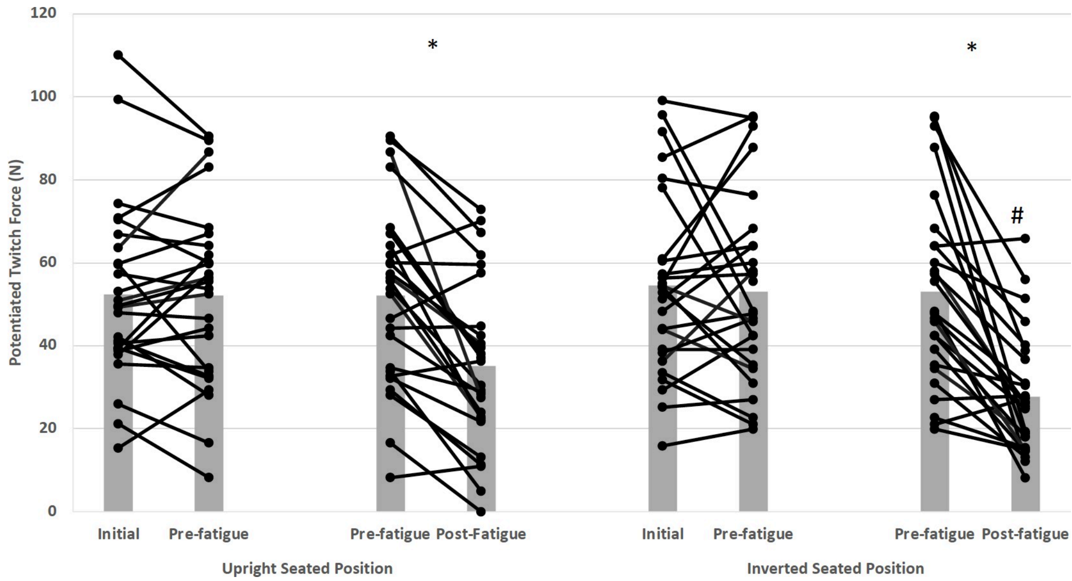

Fig 7. Potentiation Twitch Force (PTF) interaction effects for seated position and time. Star (*) symbol represents that significant Potentiation Twitch Force decreases between pre- and post-fatigue tests, for upright and inverted seated positions. The hashtag or number symbol (#) indicates that PTF tested with inversion post-fatigue was significantly lower than all other times and conditions. Means and standard deviations are illustrated. There was no statistically significant BFR interaction.

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20–40 s intervals (-32.6% (0.61 to 0.46) without BFR and 13.6%↑ (1.46 to 1.69) for BFR upright positions, versus 7.8%↑ (2.69 to 2.92) and 3.2%↑ (2.38 to 2.46) for inverted without BFR and BFR conditions), and between 40–60 s and post-30-s MVC (77.5%↑ (0.38 to 1.69)) and 35.2%↑ (1.84 to 2.84) for upright without BFR and BFR versus 13.9%↑ (2.84 to 3.30) and 26%↑ (2.61 to 3.53) for inverted without BFR and BFR conditions).

A main effect for time ($F_{(1.37,\ 16.49)} = 11.39$, $p = 0.002$, $\eta_p^2 = 0.48$) showed 34.6% ($\eta_p^2 = 0.45$, initial<pre-30-s MVC), 14% ($\eta_p^2 = 0.26$, pre-30-s MVC<0–20 s interval), and 32.3% ($\eta_p^2 = 0.49$, 40–60 s interval<post-30-s MVC) pain scale increases. Main effects for seated position and BFR showed 26.5% (upright<inversion) ($F_{(1,12)} = 14.56$, $p = 0.002$, $\eta_p^2 = 0.54$) and 15.6% increases (without BFR<BFR) ($F_{(1,12)} = 7.85$, $p = 0.01$, $\eta_p^2 = 0.39$) for pain scale.

Discussion

Prior studies have reported upon the deficits related to global (whole body) effects of inversion-induced changes in hydrostatic pressure [1–5]. Similarly, there is a body of literature exhibiting impairments associated with local (muscle group) BFR-induced increases in perfusion pressure [10,14,18,19]. The present study is the first to investigate the separate and combined effects of inversion (increased hydrostatic pressure) and BFR (increased perfusion pressure) on voluntary and evoked contractile properties. Major findings of this study were that inversion induced significantly greater decreases in resting twitch and elbow flexors MVC forces before the 30-s MVC task. Following the 30-s MVC task, inversion induced greater decreases in PTF. BFR led to overall (inversion and upright) detriments in MVC force, as well as greater decreases than without BFR while in the inverted position. Furthermore, there was a greater decrease in M-wave amplitude for the upright versus inverted position. In addition, the concomitant application of inversion of the participant with BFR of the elbow flexors only amplified neuromuscular performance impairments to a small degree. Representative traces of the measures are presented in Fig 2.

Inversion effects

Evoked contractile properties. Significant reductions in pre-test evoked twitch force with inversion are partially in accord with a previous inversion study that showed non-significant, but moderate magnitude decreases (18.6%, effect size [ES] = 0.74) for elbow flexors resting twitch force from upright to the inverted position contrasting with non-significant moderate magnitude increases (17.5%, ES = 0.76) for knee extensors [3]. Similarly, greater 30-s MVC-induced PTF decreases with inversion versus upright, in this research, also conforms with Neary et al. [3], who showed non-significant ($p = 0.06$), small magnitude, decreases for elbow flexor PTF (11.8%, ES = 0.44); whereas they reported large magnitude increases ($p = 0.03$, ES = 1.27, 27.3%) for leg extensor PTF forces during seated inversion.

With inversion, the position of the arm and leg induces higher and lower hydrostatic pressure respectively, hence contributing to the contrasting arm and leg responses in the Neary et al. [3] study. With high gravitational pressure, previous animal studies have shown an altered function of acetylcholine receptors [8], relative decrease in psoas single muscle fibre isometric force [6], decreased tetanic force for extensor digitorum longus muscle [9], and decreased Ca^{++} influx into the nerve terminal [7]. In humans, Sundberg and Kaisjer [10] showed that a graded occluded lower limb (up to 50 mmHg to increase pressure) under upright conditions caused a progressive decrease in muscle function. These results suggest higher hydrostatic or perfusion pressures on the arm during inversion can significantly reduce evoked forces.

In contrast, Paddock and Behm [4] reported no significant alterations to evoked twitch properties with seated inversion. In the Paddock and Behm study, only male subjects were recruited, and they spent 30-s rather than 1-min in the inverted position. In addition, after each contraction, the participants were returned to an upright position for 2-minutes before adopting the inverted position again for another series of voluntary and evoked contractions. Hence, the differences in duration and recovery from inversion may have attenuated changes in hydrostatic pressure while sex differences may have contributed to the differences in evoked twitch property results.

Voluntary contractile properties. The 21.1% inversion-induced MVC force decrease in the present study aligns with the 18.9–21.1%, 10.4%, and 6.1% impairments reported by Johar et al. [2], Hearn et al. [1] and Paddock and Behm [4], respectively. It might be argued that the relatively less substantial force decreases experienced by the participants in the Hearn et al. [1] and Paddock and Behm [4] studies may be attributed to shorter durations of inversion (30-s or less in each study) with 2-min recovery periods to an upright position between each MVC. However, Johar and colleagues had very similar force decreases as the present study and had participants exert MVCs for 6-s following rapid rotations of 1- or 3-s to an inverted position. Thus, MVCs were competed in less than 10-s in the Johar et al. [2] study. Neary et al. [3] reported no significant change in elbow flexor MVC force, which might be attributed to the highly trained track and field (athletics) athletes recruited in their study, who were permitted 1-min recovery periods between contractions. Hence, the relatively lower or non-significant force decrements in the Hearn et al. [1], Paddock and Behm [4] and Neary et al. [3] studies respectively may be more related to the greater recovery periods between inversion and return to upright positions.

The decreases in elbow flexors MVC force with inversion can be related to several factors. The decreased force output can be related to a muscle stiffening mechanism, associated with a threat of instability [40], that the participants could have perceived when inverted with only straps holding them in the chair. Adkin et al. [41] found that the stiffening strategy can negatively influence voluntary movement. Increased co-contractile activity with inversion has been previously reported as a factor counteracting target force output [1,4], however there were no significant increases in triceps brachii EMG in the present study. It is possible that an increased focus on stabilizing functions of the shoulders, and trunk muscles [42], could negatively impact the force output of the elbow flexors [43,44]. A shift from mobilizing to stabilizing strategies of the neuromuscular system has been reported to contribute to force reduction [43,45].

There were no significant inversion-induced decrements in biceps brachii EMG, which contrasts with 21.7%-35.9%, 26.6%, 47.9% decreases with Johar et al. [2], Paddock and Behm [4] and Hearn et al. [1] studies, respectively. As mentioned previously, these contrasts may be attributed to the greater inversion and contraction recovery periods or recruited population (i.e., track and field athletes) in the cited studies. Hence, while these other studies postulated inversion-induced neural inhibition due to increases in cerebral blood pooling and intracranial pressure [46–48], or attenuated sympathetic drive [18,46,49–51], the lack of EMG and ITT changes in the present study suggests that neural influences did not play a major role in MVC force reductions. Voluntary activation (ITT) was decreased following the 30-s MVC for both BFR and no-BFR but EMG did not significantly change. The curvilinear nature of the EMG-force relationship often resulting in a plateau at high voluntary forces diminishes the EMG sensitivity to force changes at high contraction intensities [25].

Blood Flow Restriction (BFR)

Voluntary and evoked contractile properties. Overall, BFR induced 4.8% lower MVC force values than without BFR as well as 9.1% lower MVC forces with BFR in an inverted position versus without BFR. This relative impairment is similar to the BFR-induced deficits for time to peak twitch. Without BFR, time to peak twitch increased 3.9% versus BFR when upright versus a 5.6% decrease with BFR vs. without BFR when inverted. Overall, BFR also impaired M-wave amplitudes by 21% (30.4% and 12.5% deficits for upright, and inverted seated positions respectively) compared to without BFR.

These findings are similar to the force [10] and neuromuscular efficiency deficits reported by Hobbs and McCloskey [19] with graded ischaemia. Ischaemia and the associated pain can contribute to central nervous system inhibition [15,16] adversely affecting force output. Similar to inversion, the occlusion of venous blood flow return would increase hydrostatic / perfusion pressure at the muscle resulting in similar force deficits seen in animals [6,9] and humans [10]. Hogan et al. [52] reported force decrements with diminished oxygen delivery to working muscle. Copithorne et al. [53] showed that BFR induced more significant decreases (~80%) in time to task failure during a sustained isometric fatiguing task, in comparison with normal blood flow condition. Furthermore, impairments in the evoked time to peak twitch and M-wave could be partly attributed to an alteration in muscle fibre conduction velocity [54] with nerve compression [55] as well as impaired sarcoplasmic reticulum Ca^{2+} uptake [56]. With median nerve compression in the carpal tunnel, Lunderborg et al. [57] observed a change in endoneural microcirculation. While it would be logical to suspect peripheral alterations with BFR, central responses can also be influenced.

The greater BFR-induced decrease ($p = 0.07$, 16.4%) in biceps brachii EMG versus without BFR (7.9%) may reflect a greater hypoxia placing a greater emphasis on anaerobic metabolism, resulting in an earlier higher threshold motor unit recruitment accelerating the onset of force decrements [58,59]. Occluding arterial flow in the arm, during the post-exercise period, Bigland-Ritchie et al. [15] observed an impairment of neuromuscular transmission.

The modest but significant decrements in MVC force (<5%) and only near significant ($p = 0.07$) changes in EMG activity with blood flow occlusion from a blood pressure cuff might be attributed to the occlusion effects from the MVC. Since a MVC also contributes to BFR, the additional effect of the blood pressure cuff on a maximal contraction might not have been as prominent as it might be with submaximal contractions.

Perceived pain. Previous seated inversion studies [2–4] have mentioned that there was a sense of discomfort (i.e., distinct swelling around the head region) during inversion but did not directly measure or report the degree of discomfort. Overall, pain perception tended to be higher with BFR (15.6%) as well as when inverted (26.5%). Increased pain perception with inversion would be related to the increased hydrostatic pressure around the head region (Paddock and Behm 2009). BFR would induce a hypoxic muscle environment resulting in a greater reliance on anaerobic metabolism, higher accumulation of metabolites and with the BFR, an inability to dispose these metabolites [10,52]. A compressed limb can lead to ischaemia accumulating metabolites and with increased local acidity would activate group III and IV pain afferents promoting a sensation of increased discomfort and pain [17,20,60].

Inversion and BFR interactions. The data tended to indicate that BFR with inversion induced small (~5–12.5%) multiplicative effects upon voluntary and evoked muscle force and activation. A non-significant (p = 0.07) but large partial eta^2 magnitude BFR x inversion interaction showed that evoked twitch forces had a BFR-induced greater increase (5.6%) than without BFR in the inverted position. In contrast, MVC forces with BFR showed greater decreases (-9.1%) than without BFR for the inverted seated position. The M-wave amplitude was more impaired by BFR (-12.5%) than without BFR in the inverted position. Finally, pain perception increased with BFR (11.1%) versus without BFR with the inverted position. Thus, the combination of inversion and BFR provided some amplification of the deficits compared to inversion alone (i.e., decreased elbow flexor resting twitch and MVC forces). The BFR-induced hypoxic environment attenuates blood substrates leading to a greater accumulation of metabolic by-products that could negatively impact force production. On the other hand, BFR may increase neuromuscular excitation (i.e., increased M-wave amplitudes). Neural compression and blood flow impairment have elevated EMG with submaximal contractions [61,62]. Copithorne et al. [53] reported that blood flow occlusion led to a more rapid and greater increase in motoneuron excitability but had no effect on motor cortical excitability suggesting that group III/IV afferent feedback was the primary cause of the enhanced motoneuron excitability. Thus, BFR can induce both peripheral impairments and central excitation. These contrasting effects in combination with inversion-induced (i.e., increased hydrostatic pressure) alterations provided small but not major amplification of the deficits.

There were some minor limitations to the research. Due to the research procedure, data could only be obtained from the right limb. While the partial BFR was set relative to the position (upright/inverted), it could not exclusively indicate 50% BFR upright was exactly the same as inverted. Furthermore, female participants were not screened for birth control or menstrual cycle phase, which could have affected the performance of some of the women. As the present study recruited active adults who resistance trained on a consistent basis, we would hypothesize that the observed impairments might be more substantial with an untrained population with less experience coping with partial or full occlusion (e.g., moderate to high intensity contractions while resistance training) and increases in hydrostatic pressures (e.g., Valsalva maneuvers while resistance training).

Conclusions

Hydrostatic pressure-induced peripheral muscle impairments with the inverted position, may have contributed to decreases in elbow flexor twitch, PTF, and MVC forces before the fatigue task. BFR did decrease voluntary force and M-wave amplitudes with only a small additional increase to the inversion-induced impediments. A decrease in force or power output, with an increased perceived difficulty in stressful and life-threatening conditions such as accidents involving inversion or blood flow restriction (i.e., overturned vehicles, aerial maneuvers) can be life threatening. The results provide insights into the separate and combined effects of global (inversion) and local (BFR) increases in hydrostatic/perfusion pressure on voluntary and evoked contractile properties.

Author Contributions

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Funding acquisition: David G. Behm.

Investigation: Hamid Ahmadi.

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Project administration: Hamid Ahmadi.

Supervision: Duane C. Button, David G. Behm.

Writing – original draft: Hamid Ahmadi.

Writing – review & editing: Nehara Herat, Shahab Alizadeh, Duane C. Button, Urs Granacher, David G. Behm.

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