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Title:

Explosive Voluntary Torque is Related to Whole-body Response to Unexpected Perturbations

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FB, MTGP and JPF all contributed to study design, data acquisition, analysis, interpretation and article drafting and revising. All authors have read and approved the final submitted manuscript.

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Abstract

Explosive torque has been demonstrated to relate to static balance. However, sports injuries occur dynamically and unpredictably, yet the relationship between explosive torque and balance response to dynamic perturbations is unknown. This study investigated the relationship between explosive torque of the plantar flexors and knee extensors and the centre of mass (COM) response to unexpected perturbations. Thirty-three healthy subjects (17 females, 16 males) were assessed for maximal and explosive isometric knee extension (KE) and plantar flexion (PF) torque and COM response (velocity (COMV), displacement (COMD)) to unexpected platform translations. Relationships between explosive torque and balance measures were investigated using Pearson's correlation and multiple regression. A negative relationship between PF explosive torque at 50, 100, and 150 ms and COMV at 300, 400, and 500 ms (r =-0.363 to -0.508, $p \leq 0.049$), and COMD at 400 and 500 ms (r=-0.349 to -0.416, $p \leq 0.046$) was revealed. A negative relationship between KE explosive torque at 50, 100, and 150 ms and COMV at 400 ms (r = -0.381 to -0.411, $p \leq 0.029$) but not COMD was also revealed. Multiple regression found PF 100 ms predicted 17.3% of variability in COMD at 500 ms and 25.8% of variability in COMV at 400 ms. These results suggest that producing torque rapidly may improve COM response to unexpected perturbation.

Introduction

Sporting participation has obvious physical, social and psychological benefits but contains significant musculoskeletal injury risk (Bahr and Holm, 2003). An anterior cruciate ligament (ACL) rupture is one of the most common and costly sports injuries (Domire et al., 2001). It has been estimated that an ACL injury ages the knee 30 years and individuals who suffer a knee injury are at a more than 5-fold greater increase of developing osteoarthritis (Butler et al., 2008). Therefore, investigating potential contributors to injury mechanisms that may guide novel preventative strategies remain important.

ACL injuries occur within 50 ms of foot contact (Krosshaug et al., 2007) thus the ability to produce muscular force rapidly may be important in stabilising joints and preventing injurious positions (Zebis et al., 2010). The muscular ability to produce force rapidly is commonly referred to as explosive torque/force (i.e. at specific time points) or rate of torque/force development (RTD/RFD; i.e. gradient over specific periods). Explosive torque has been investigated in many populations (males, females, elderly, performance athletes) and demonstrated to be a determinant of athletic performance (Tillin et al., 2013; West et al., 2011). Post ACL repair, the ability to produce torque explosively has been demonstrated to predict hopping and vertical jump performance (Pua et al., 2017), to display larger asymmetries than maximal strength (Knezevic et al., 2014), and to be associated with self-reported knee function (Hsieh et al., 2014). However, there has been limited research into the relationship between explosive torque and balance performance. Explosive torque has been related to sway index (r = -0.559, p = 0.010) (Palmer et al., 2014) and RTD to balance measures in elderly subjects (Ema et al., 2016; Izquierdo et al., 1999]. RTD measures have also been found to predict tests that challenge lateral stability (Chang et al., 2005) and discriminate between elderly fallers and non-fallers (Bento et al., 2010, Pjinappels et al., 2008). Collectively these results suggest that the ability to produce torque explosively may be related to balance performance and falls prevention.

Sports injuries occur in dynamic, unpredictable situations and often involve unexpected perturbations due to collision or impact (Krosshaug et al., 2007). Therefore, relationships between explosive force and static balance measures, such as sway index (Palmer et al., 2014), or premeditated balance tasks (Izquierdo et al., 1999) do not address the ability to control body position and balance in response to unexpected dynamic perturbations that occur within sports. Explosive torque has been demonstrated to improve dynamic balance recovery restricted to utilising the ankle strategy (Robinovitch et al., 2002) but has not been investigated with a whole-body response replicating the sporting environment. Accordingly, this study aimed to investigate whether knee extensor and plantar flexor explosive torque were related to the ability to stabilise the COM in response to unexpected perturbations. It was hypothesised that greater explosive muscular torque would be related to lower COM motions to unexpected perturbations.

Methods

Participants

Thirty-three healthy, young, participants (17 females: age 22.9 ± 3.1yr, height 1.66 ± 0.06m, mass 65.0 ± 8.3kg; 16 males: age 24.7 ± 5.1, height 1.81 ± 0.09m, mass 81.1 ± 9.5) provided written informed consent prior to participating in this study, which was approved by the Loughborough University Ethical Approvals Committee. Participants had a BMI of ≤ 26 $kg.m^{-2}$, no history of traumatic lower limb injury or current musculoskeletal condition and were not involved in systematic physical training. Body mass and height were measured using a calibrated scale and stadiometer (Seca, Hamburg, Germany). All participants had moderate levels of physical activity as assessed by the International Physical Activity Questionnaire (iPAQ) (Craig et al., 2003). Participants were advised not to undertake any unaccustomed/strenuous physical activity for 36 hours prior to testing and to have eaten and drunk normally. To control for the possibility of menstrual cycle phase influencing neuromuscular performance during testing females were required to have been taking the combined monophasic oral contraceptive pill for >6 months and were tested between days 7 and 21 of pill consumption to minimize any fluctuations in endogenous gonadal hormones (Pearson et al., 2011).

Study Design

This study used a cross-sectional study design. Participants visited the laboratory twice, separated by 5-10 days, for a familiarisation session and a main trial. Sessions commenced between 11.30am and 4.30pm. Familiarisation involved participants completing isometric contractions of the plantar flexors (PF) on an adapted commercial dynamometer and knee extensors (KE) on a custom built isometric strength testing chair; followed by familiarisation with dynamic perturbation testing. The main trial involved the same muscle function tasks of both legs unilaterally, first PF and then KE measurements, followed by assessment of the whole-body perturbation response to unexpected platform movements.

Muscle Function Measurements

Plantar Flexion: Participants were secured in an adapted commercial dynamometer (Con-trex, Dubendorf, Switzerland) in a kneeling position with a custom upright to support the anterior thigh, lock the proximal shank and minimise extraneous movement (Appendix 1A). The dynamometer fulcrum was positioned in line with the lateral malleolus and the ankle was fixed at 90º and the knee at 120º (180º = full extension). Three ankle straps were secured tightly with a hip strap to further minimise any extraneous movements. The torque signal from the dynamometer was amplified (x1000) and sampled at 2000 Hz using an external A/D converter (Micro 1401; CED, Cambridge, UK) interfaced with a PC running Spike 2 software (CED Ltd., Cambridge, UK). In offline analysis, torque data were low-pass filtered at 500 Hz using a fourth-order zero-lag Butterworth filter.

Knee Extension: Participants were secured in a customised dynamometer (Maffiuletti et al., 2016) with hip and knee joint angles of 125º and 115º respectively (Appendix 1B). Adjustable strapping across the pelvis and shoulders prevented extraneous movement. A strap, 40mm width of reinforced canvas webbing, was placed proximal to the ankle (~15% of tibial length above medial malleolus) in series with a calibrated S-beam strain gauge (Force Logic, Swallowfield, UK). The analogue force signal from the strain gauge was amplified (x370) and sampled at 2000 Hz using an external A/D converter (Micro 1401; CED, Cambridge, UK) interfaced with a PC running Spike 2 software (CED Ltd., Cambridge, UK). In offline analysis, force data were low-pass filtered at 500 Hz using a fourth-order zero-lag Butterworth filter, gravity corrected by subtracting baseline force, and multiplied by lever length (distance from ankle strap centre to knee joint space) to calculate torque (Balshaw et al., 2016).

Protocol

Maximum Voluntary Isometric Contractions: Participants performed a series of warm-up contractions at ~50% and ~75% of perceived maximum voluntary torque (MVT) followed by three maximum voluntary contractions (MVCs) each lasting 3s with >30 s rest between.

Participants were instructed to contract as hard as possible and motivated with a standardised script of verbal encouragement and real-time visual biofeedback of the force response of each contraction. MVT was defined as the greatest torque during any MVC or explosive contraction.

Explosive Voluntary Isometric Contractions: Following a 2-minute rest post MVCs, participants completed 10 explosive KE and PF contractions, separated by 20s. They were instructed to contract ‘as fast and as hard as possible’ for 1s with ‘fast’ emphasized. To provide biofeedback on their explosive performance the slope of the force time curve was displayed throughout the contractions, with the peak slope of their best attempt highlighted. Contractions associated with pre-tension or a counter movement were discarded and repeated. A visual marker on screen depicted 80% MVT during the explosive contractions and participants were instructed to achieve this level in order to ensure a forceful contraction. Explosive contractions were performed until 10 contractions met criteria. Torque onset was defined manually by visual identification by one trained investigator; this involved viewing torque on an x axis scale of 300 ms prior to contraction and on a y axis scale of 0.68 N.m, before zooming in to determine the instant of the final trough or peak before the signal deflected away from the envelope of baseline noise (Balshaw et al., 2016). Explosive voluntary torque (EVT) was measured at discrete time points: 50, 100, and 150 ms from torque onset during the explosive contractions (e.g. PF 50, PF 100 etc.). All torque measures were normalised to body mass (kg) for correlations and regression analysis.

Perturbation Response Testing

Perturbation trials were completed on a CAREN system (Computer Assisted Rehabilitation Environment, Motek Medical, Amsterdam, Netherlands), a computer controlled Stewart platform that can independently perturb the support surfaces in each of the six degrees of freedom. It has been found to be highly reliable for use in postural and balance research.[19] Prior to the perturbations 57 spherical markers of 14 mm diameter were attached to the participants to facilitate collection of kinematic data at 200 Hz using 9 T20 Vicon (Vicon, Oxford Metrics Group, UK) cameras. Whole-body segmental anthropometric measurements involved 45 measurements of each participant according to a reduced set inertial model (Yeadon, 1990). These were utilised to calculate participant-specific segmental inertial parameters for 15 body segments and used in the determination of joint centre locations and segmental and whole-body COM.

The COM position was defined relative to the centre of the platform, specifically the mean position of 4 markers located at the corners of the force plate. Participants were instructed to stand upright on the CAREN platform with hands by their side, the non-standing foot in a standardised position, the forefoot lightly touching the standing ankle, and asked to try to remain stationary and not to take a step in response to the perturbation. The perturbation commenced at random after participants had confirmed they were stable. Single leg standing was chosen to provide a sufficient balance stimulus. Four experimental conditions, sequentially in the following order: right foot/eyes open, left foot/eyes open, right foot/eyes closed, left foot/eyes closed, were completed with 16 trials per experimental set, resulting in 64 trials per subject. The direction order of each perturbation (left, right, forward, backward) was block randomised so that 4 of each direction occurred in each experimental set. Only anterior platform displacements were analysed (including eyes open and closed) to assess sagittal plane muscle function, with the other directions interspersed to reduce predictability. This resulted in 16 anterior trials per participant, with the average of these trials used for analysis. The perturbations were controlled by a custom script written in the Motek Medical

D-Flow software. Anterior platform perturbations had a magnitude of 0.1 m and a maximum velocity of 0.3 m.s^{-1} (Figure 1). The order of platform directional perturbations was selected randomly during pilot testing and was consistent for all participants. Data were low pass filtered with a fourth-order zero-lag Butterworth filter using a cut off frequency of 15 Hz. Initiation of perturbation was defined as when the velocity of the platform markers exceeded 0.005 m.s^{-1}. COM displacement and velocity (over 5 ms time periods) were obtained from the initiation of perturbation to 500 ms post perturbation using Visual3D software (C-motion, Germantown, MD, USA) with values at 100 ms intervals used for analysis. COM displacement (COMD) after the onset of the perturbation was measured relative to the initial position at onset of perturbation (defined as 0), and COM velocity (COMV) was defined as instantaneous velocity at each frame.

Statistical Analysis

Average measures across right and left legs were utilised for statistical robustness. The relationship of KE and PF MVT and EVT (at time points 50, 100, and 150 ms after contraction onset) with COMV and COMD values (100 ms intervals up to 500 ms) were investigated using Pearson’s correlation coefficients. Subsequently stepwise multiple regressions were undertaken to examine the influence of the entered predictor variables (isometric strength parameters that displayed highest correlations with criterion variables) that independently explained a proportion of the total variance of COMD and COMV (criterion variables). Between subject coefficient of variation (CV) was obtained by calculating the ratio of the standard deviation to the mean. Statistical significance was defined as $p < 0.05$. All statistical procedures were performed with IBM SPSS Statistics for Windows (Version 22.0, NY, USA, IBM Corp.).

Results

Descriptive Data for Torque and Perturbation Measures

EVT increased progressively throughout the first 150 ms of explosive contractions for both muscle groups: KE EVT rose from 0.65 N.m.kg^{-1} at 50 ms (CV 55%) to 2.26 N.m.kg^{-1} at 150 ms (CV 32%) and PF EVT increased from 0.38 N.m.kg^{-1} at 50 ms (CV 42%) to 1.82 N.m.kg^{-1} at 150 ms (CV 23%; Figure 2).

During the first 500 ms of anterior perturbations, the COMD relative to the base of support (the platform) at onset was increasingly posterior (0.005 m at 100 ms (CV 23%) up to 0.07 m after 500 ms (CV 15%), positive displacement value indicates posterior COMD). Consequently, there was an increasing posterior COMV during the initial phase of perturbation, on average peaking 300 ms after perturbation (CV 13%), before decreasing (decelerating) and becoming an anterior velocity after 500 ms (Figure 3).

Bivariate Correlations of PF Torque with COMD and COMV

PF EVT at all time points exhibited weak to moderate correlations with COMD in the later phase of the perturbation (PF 50 ms and COMD at 500 ms, $r = -0.380$, $p = 0.029$; PF 100 ms and COMD 400-500 ms, $r = -0.349$ to -0.416, $p \leq 0.046$, Figure 4A; PF 150 ms and COMD from 400-500 ms, $r = -0.352$ to -0.406, $p \leq 0.044$, Figure 5A). PF EVT at all time points also exhibited weak to moderate negative correlations with COMV in the later phase of the perturbation (PF 50 ms and COMV 400- 500 ms, $r = -0.421$ to -0.459, $p \leq 0.015$; PF 100 ms and COMV 400- 500 ms, $r = -0.398$ to -0.508, $p \leq 0.022$, Figure 4B; PF 150 ms and COMV 300-500 ms, $r = -0.346$ to -0.479, $p \leq 0.049$; Figure 5B). In contrast, PF MVT was unrelated to either COMV or COMD ($r = -0.053$ to -0.246, $p \geq 0.167$).

Bivariate Correlations of KE Torque with COMD and COMV

KE EVT at 50, 100, and 150 ms showed weak to moderate negative correlations with COMV at 400 ms ($r = -0.381$ to -0.411, $p \leq 0.021$, Figure 6A) but not with any measures of COMD (Figure 6B). KE MVT was negatively correlated with COMV at 300 ms ($r = -0.371$, $p = 0.033$) but not with COMD ($r = -0.199$ to -0.288, $p \geq 0.104$).

Multiple Regression Analysis

The muscle function measurements that were the strongest predictors of perturbation response for each muscle group (PF 100 and KE 100) from the correlation analysis were subsequently included in a stepwise multiple linear regression analysis. PF 100 predicted 17.3% of the variability in COMD at 500 ms and 25.8% of the variability in COMV at 400 ms. KE 100 was not found to be a significant predictor of COMD or COMV within the multiple regression analysis.

Discussion

The present study investigated the relationship between the COM stabilisation (displacement/velocity) in response to unexpected anterior perturbations with both KE and PF explosive torque. PF EVT had weak to moderate correlations with COMD from 400-500 ms (r = -0.346 to -0.508) and COMV from 300-500 ms (r = -0.349 to -0.416; i.e. more explosive torque less COMD and COMV), with weaker correlations between KE EVT and COMV at 400 ms (r = -0.381 to -0.411) but not with COMD. In contrast MVT of the PF and KE were unrelated to COMD and unrelated/ weakly related to COMV. Moreover, the regression analysis revealed PF 100 to be the only neuromuscular variable to independently contribute to the explained variance in COMD and COMV.

These findings suggest that greater explosive torque, particularly from the distal (PF) musculature, results in better control of the COM in response to unexpected perturbations. PF EVT explained up to 25.8% of the variability in the COMD following perturbation. Thus, while PF EVT was the primary neuromuscular determinant of the ability to respond to unexpected perturbation, the majority of the variance remained unexplained. Somatosensory and reflex responses might also be expected to contribute substantially to the perturbation response. Nonetheless, in the current study significant correlations were consistently found for explosive torque measured at a range of time points, with both COMV and COMD from 300-500 ms indicating a genuine, systematic relationship.

Our findings of a negative relationship between explosive torque and COM response substantiates previous research that found higher explosive torque to be related to superior static or premeditated balance responses (Ema et al., 2016; Izquierdo et al., 1999; Jakobsen et al., 2011; Palmer et al., 2014; Sundstrup et al., 2010). In overview, there is accumulating evidence that lower limb explosive torque production may improve the ability to recover balance and appears to be an important component of falls risk and injury prevention (Bento et al., 2010; Jakobsen et al., 2011; Sundstrup et al., 2010).

Repeated significant correlations were found between PF EVT and both COMV and COMD providing evidence of a consistent relationship, however, KE EVT only correlated with COMV at 400 ms and not with any COMD values, presumably because the KE did not sufficiently influence COMV to effect COMD. Furthermore, PF EVT was the only predictor of COM response in stepwise regression. Therefore, PF explosive torque appears more important in controlling dynamic perturbation response. The greater importance of the PF may be a consequence of a distal to proximal muscle activation pattern in response to perturbations, where postural muscle activation begins at the base of support (Alexander et al., 1992; Jakobsen et al., 2011; Sveistrup et al., 1997). A greater contribution of the ankle musculature and a lesser contribution of the knee musculature in achieving postural control in response to perturbation is in accordance with previous literature (Hall and Jensen, 2002; Jakobsen et al., 2011).

In contrast to PF explosive torque PF MVT was not correlated with either COMD or COMV. Other studies have also found weaker or no relationship for MVT and balance performance, compared to EVT (Bento et al., 2010; Izquierdo et al., 1999; Lee et al., 2009). As maximal torque can take more than 300 ms to produce it seems that explosive torque may be more pertinent in response to rapid stimuli such as unexpected perturbations and sports related injury mechanisms (Krosshaug et al., 2007; Sundstrup et al., 2010). The relationship between EVT, and not MVT, to perturbation response demonstrates that explosive torque production, rather than maximal torque, appears the most important neuromuscular characteristic in responding to rapid alterations to postural balance. Therefore, future interventions for improving postural balance response may benefit from including specifically explosive strength training, rather than training for maximal strength.

Correlations between PF/KE explosive torque and COM response to perturbation only became significant from 300 ms onwards. The anterior platform perturbation caused the COM to initially move posteriorly relative to the base of support/platform (Nashner et al., 1979), before participants initiated a response to prevent the COM moving outside, and in this case posterior to, the base of support (Lin and Woolacott, 2002). Considering muscle response latency, potentially over 100 ms (Nashner et al., 1979) including sensory and neurological delays, followed by electromechanical delay (Blenkinsop et al., 2016), it is feasible that the initiation of compensatory muscular torque only commenced 150 ms after the perturbation. Thereafter muscular torque would have progressed rapidly to slow and ultimately reverse the posterior velocity of the COM imposed by the anterior platform displacement. This potential reversal of COMV consequently exhibited a reduction in COMD from 400 ms; implying reactive torque may have reduced the COM displacement from the perturbing mechanism.

Many sporting injuries, such as ACL injuries, are in response to an activity involving an initial contact, such as landing and changing direction (Krosshaug et al., 2007). Therefore, future research should attempt to replicate the current findings in a sporting specific scenario to confirm the relationship between explosive torque and kinematic responses following a task such as landing from a jump or changing direction. The current investigation may have been limited by utilising isometric contractions, while facilitating controlled measurements of maximum and explosive torque, this measurement may lack ecological validity to dynamic functional movement. The current findings would also have been more robust with a larger number of participants. In conclusion, the ability to produce torque rapidly in the PF was moderately associated with the response to unexpected perturbations, predicting up to 26% of perturbation response. This indicates that higher explosive torque capacity, which can be developed through training (Balshaw et al., 2016), may be useful in responding to external collisions and disturbances of balance, and would be expected to reduce injury risk in sporting situations.

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Conflict of interest statement

This is to confirm the authors of this work have no conflicts of interest.

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Figure 1. Platform trajectory during an anterior perturbation showing (A) anterior displacement and (B) velocity.

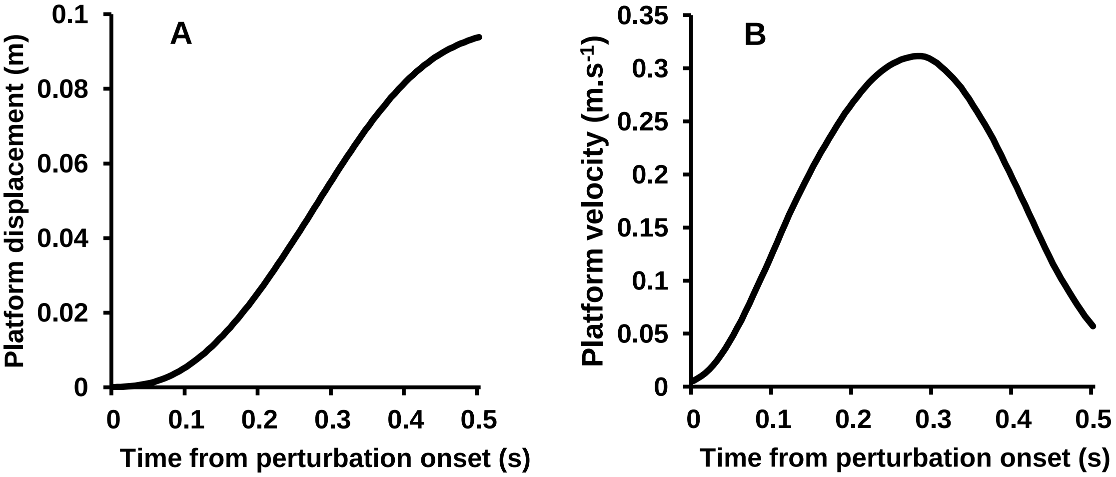
Figure 2. Explosive knee extensor (A, black squares) and plantar flexor (B, black circles) torque for each measured time point (ms). Values are mean ± SD (n = 33) with maximum and minimum values (dashed line).

Figure 3. Centre of mass (COM), (relative to centre of moving force plate) Displacement (A, black squares) and COM Velocity (B, black circles) for each time point (ms) post perturbation. Values are mean ± SD (n = 33) with maximum and minimum values (dashed line). Positive values indicate posterior displacement/velocity.

Figure 4. Sample scatter plots of PF explosive torque at 100 ms and (A) COM Displacement at 400 ms and (B) COM Velocity at 400 ms (n = 33).

Figure 5. Pearson’s product moment correlation coefficients between explosive torque of the plantar flexors (PF) at three time points (50, 100, 150) and centre of mass displacement (COMD, A) and centre of mass velocity (COMV, B) post perturbation (n = 33). Y axis inverted for ease of visualization.

Figure 6. Pearson’s product moment correlation coefficient between explosive torque of the knee extensors (KE) at three time points (50, 100, 150) and centre of mass displacement (COMD) (A) and centre of mass velocity (COMV) (B) post perturbation (n = 33). Y axis inverted for ease of visualization.


A
Platform displacement (m)
0.1
0.08
0.06
0.04
0.02
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0
0.1
0.2
0.3
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0.5
Time from perturbation onset (s)
B
Platform velocity (m.s-1)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.1
0.2
0.3
0.4
0.5
Time from perturbation onset (s)

Figure 1.

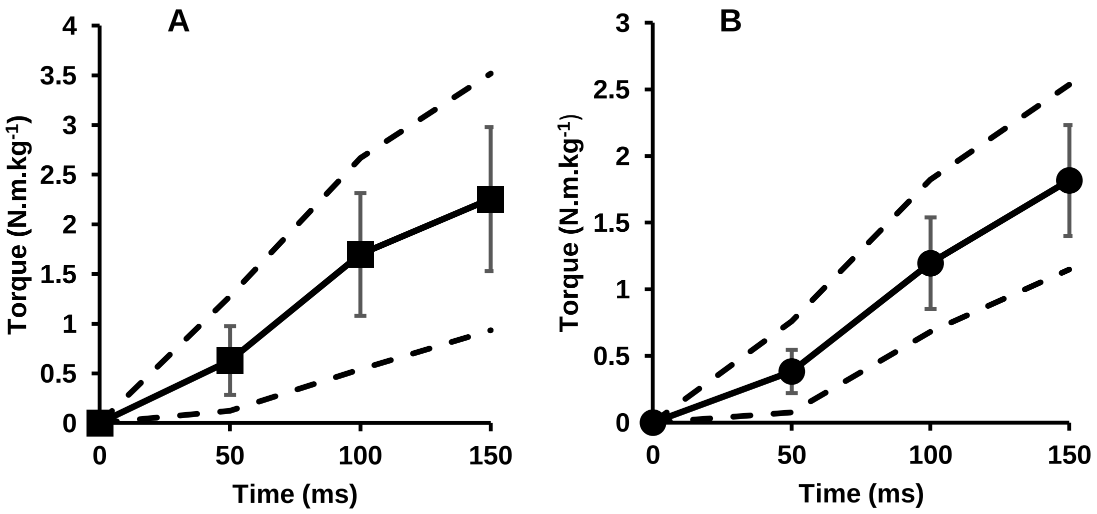

A
Torque (N.m.kg-1)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
50
100
150
Time (ms)
B
Torque (N.m.kg-1)
3
2.5
2
1.5
1
0.5
0
0
50
100
150
Time (ms)

Figure 2.

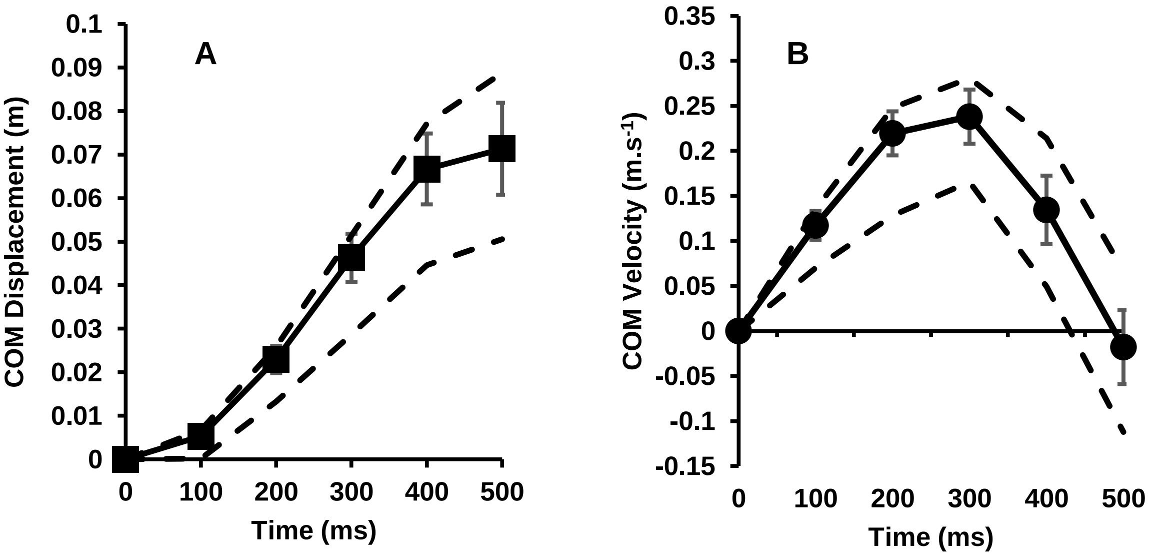

A
COM Displacement (m)
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
100
200
300
400
500
Time (ms)
B
COM Velocity (m.s-1)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
0
100
200
300
400
500
Time (ms)

Figure 3.

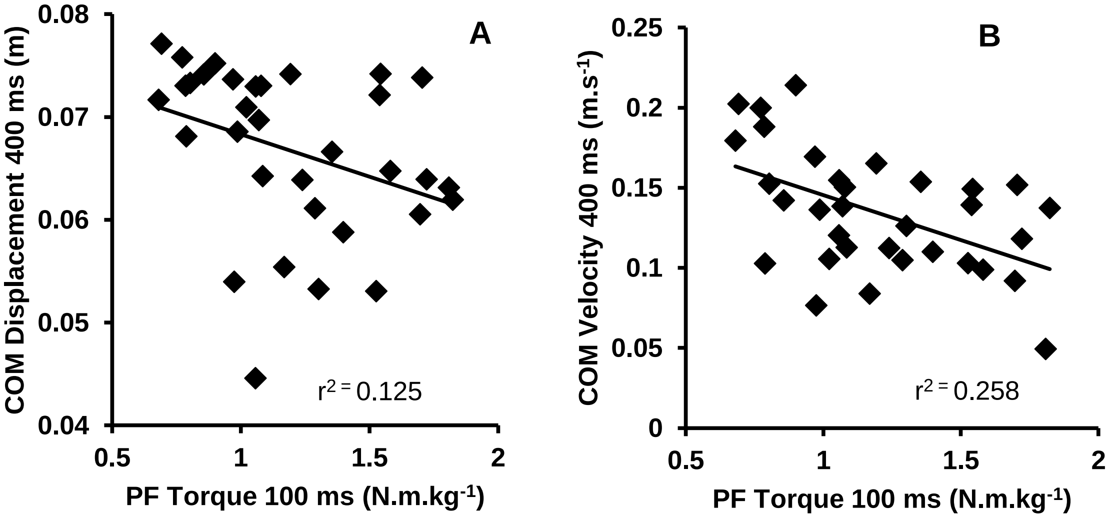
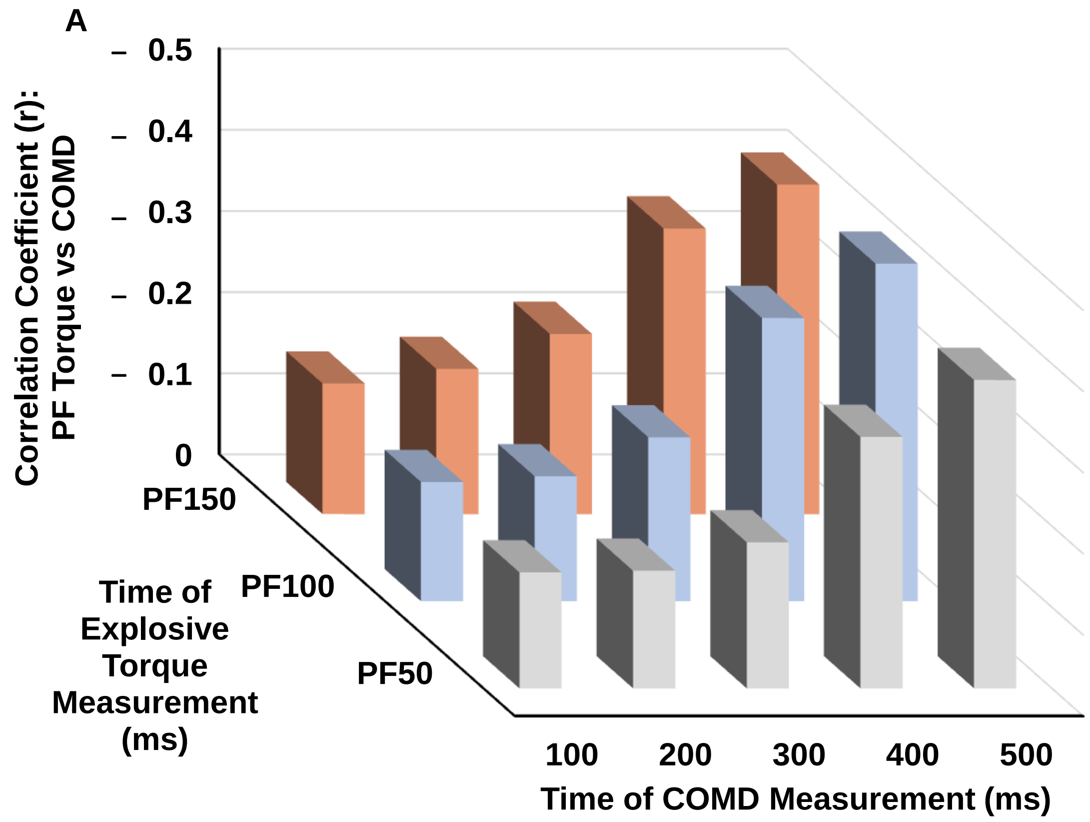

A
COM Displacement 400 ms (m)
0.08
0.07
0.06
0.05
0.04
0.5
1
1.5
2
PF Torque 100 ms (N.m.kg-1)
r2 = 0.125
B
COM Velocity 400 ms (m.s-1)
0.25
0.2
0.15
0.1
0.05
0
0.5
1
1.5
2
PF Torque 100 ms (N.m.kg-1)
r2 = 0.258

Figure 4.

Figure 5



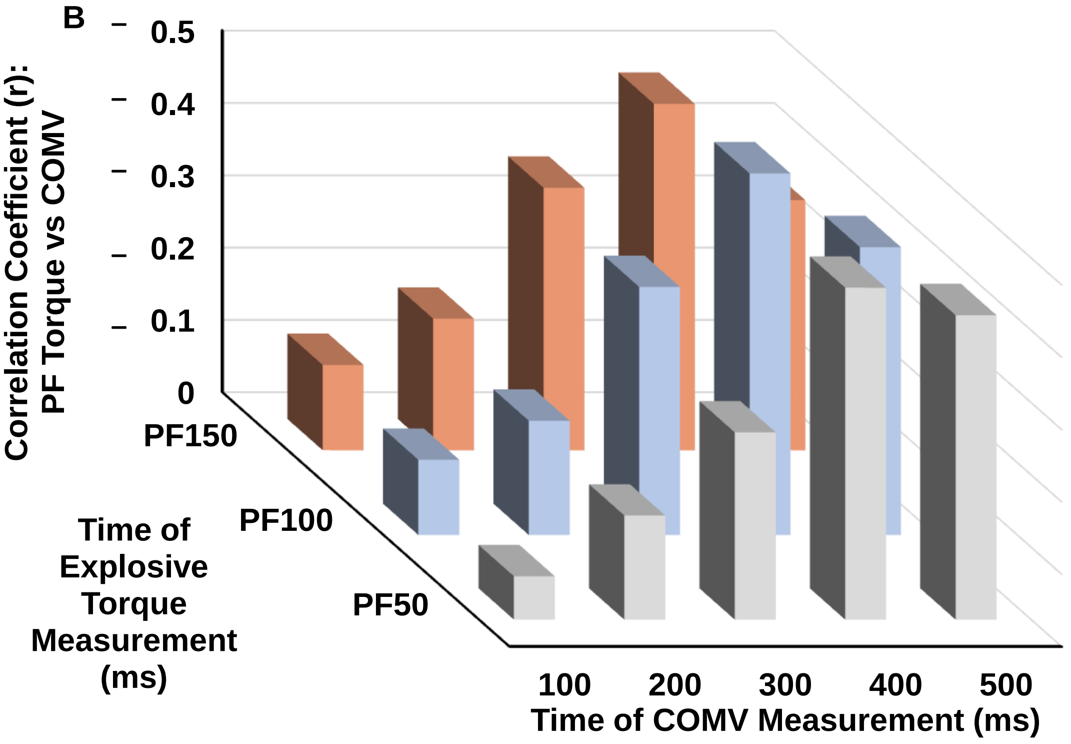


Figure 5.

Figure 6

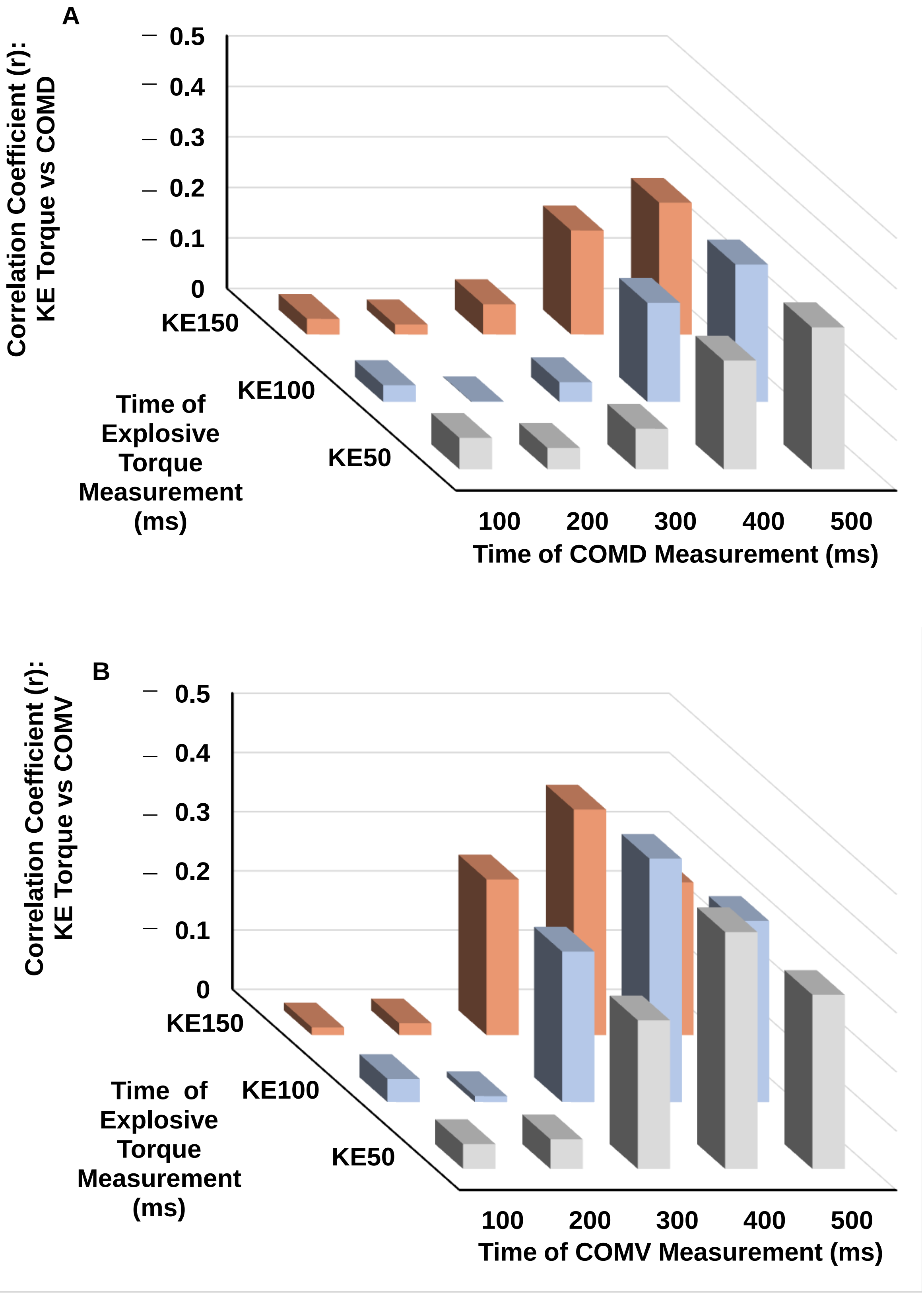
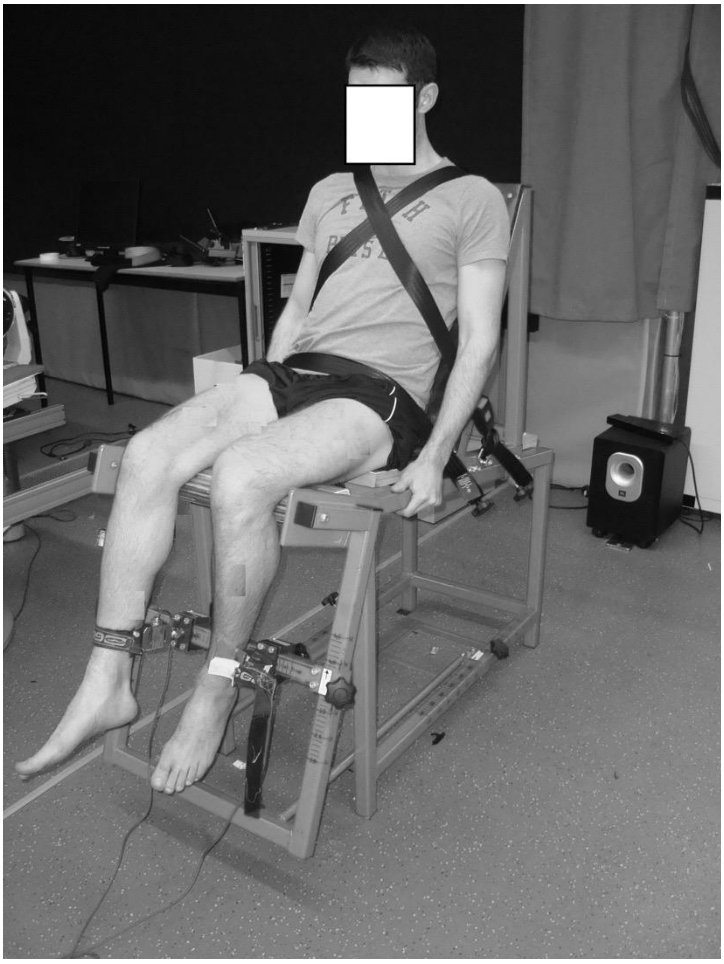


Figure 6.

Appendix 1A

Appendix 1A. Isometric maximum and explosive voluntary torque measurements of the plantar flexors with an adapted Con-trex isokinetic dynamometer.

Appendix 1B



Appendix 1B. Isometric maximum and explosive voluntary torque measurements of the knee extensors with a custom built isometric dynamometer.