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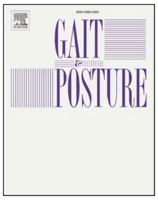

Knee extensor force control as a predictor of dynamic balance in healthy adults

Emily Mear [a], Valerie Gladwell [b], Jamie Pethick [a,*]

[a] School of Sport, Rehabilitation and Exercise Sciences, University of Essex, Essex, UK
[b] Institute of Health and Wellbeing, University of Suffolk, Suffolk, UK

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ABSTRACT

Background: Previous research has demonstrated that force control in various muscles of the lower limb (measured according to the magnitude of force fluctuations) explains significant variance in static balance. Given the dynamic nature of many functional activities and sports, assessment of balance and its determinants under dynamic conditions is of importance.
Research question: Does muscle force control explain significant variance in dynamic balance, as measured using the Y balance test (YBT)?
Methods: YBT performance and knee extensor muscle force control were measured in 28 healthy participants. The YBT involved stance on the right leg and attempting maximal reach with the left leg in the anterior, posteromedial, and posterolateral directions. Force control was assessed during isometric knee extension contractions of the right leg at 10%, 20% and 40% maximal voluntary contraction (MVC) and was quantified according to the magnitude (using the coefficient of variation [CV]), and the temporal structure (using sample entropy, SampEn; and detrended fluctuation analysis α), of force fluctuations.
Results: Significant correlations were observed for YBT anterior reach and muscle force CV ($r = -0.44$, $P = 0.02$) and SampEn ($r = 0.47$, $P = 0.012$) during contractions at 40% MVC. A subsequent regression model demonstrated that muscle force CV and SampEn at 40% MVC significantly explained 54% of variance in YBT anterior reach. Significant correlations were also observed for YBT posteromedial reach and MVC ($r = 0.39$, $P = 0.043$) and muscle force CV during contractions at 40% MVC ($r = -0.51$, $P = 0.006$). The regression model demonstrated that MVC and muscle force CV at 40% MVC significantly explained 53.9% of variance in YBT posteromedial reach.
Significance: These results are the first to indicate that a moderate amount of variance in dynamic balance can be explained by measures of isometric force control.

1. Introduction

The production of voluntary force is accomplished through precise activation of motor unit populations [1]. The resultant force (or torque when applied about a joint) exerted by a contracting muscle should, ideally, be smooth and accurate, though in fact constantly fluctuates around a prescribed target value [2]. These fluctuations can be quantified using magnitude- or complexity-based measures, with each providing unique insight into the ability to control muscle force output [3]. Magnitude-based measures, such as the standard deviation (SD) and coefficient of variation (CV), quantify the degree of deviation from a fixed point within a time-series [4] and provide an index of force steadiness. Importantly, the CV (i.e., magnitude of fluctuations normalised to the mean) is strongly associated with variance in common synaptic input to active motor neurons, the main determinant of force fluctuations [5,6]. Complexity-based measures quantify the degree of time-series irregularity (e.g., sample entropy, SampEn) [7] and identify the presence of long-rage fractal correlations (e.g., detrended fluctuation analysis α, DFA) [8]; properties which magnitude-based measures cannot quantify [9]. Complexity-based measures provide an index of adaptability; that is, the ability to modulate force output rapidly and accurately in response to task demands [10]. The use of both magnitude- and complexity-based measures is necessary for a thorough examination of muscle force control [3,9].

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* Correspondence to: School of Sport, Rehabilitation and Exercise Sciences University of Essex, Wivenhoe Park Colchester, CO4 3WA, UK.
E-mail address: jp20193@essex.ac.uk (J. Pethick).

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The fluctuations evident in muscular output are of functional significance, influencing our ability to achieve a desired force and produce an intended movement trajectory [2]. Indeed, the CV of submaximal force (during contractions at intensities <20% maximal voluntary contraction; MVC) has been demonstrated to explain significant amounts of variance in performance of tests of motor function, such as manual dexterity (wrist extensors) [11], walking (plantarflexors) [12] and static balance (plantarflexors) [13,14]. Moreover, several studies on static balance have found the CV of force fluctuations in the hip abductors and ankle dorsiflexors [15] and ankle plantarflexors [16] to be stronger predictors of task performance than maximal strength. These findings suggest that the control strategy used during submaximal contractions is related to the ability to maintain balance [15].

Balance control is, however, not amenable to characterisation by a single test [17]. Indeed, balance is commonly distinguished between static and dynamic components; with static balance referring to maintenance of static unperturbed posture and dynamic balance referring to balance control during voluntary execution of a movement [17]. Given the dynamic nature of many activities of daily living and sports, assessment of balance and its determinants under such dynamic conditions is of importance [18]. This is illustrated by the observation that risk of falling is more closely related to dynamic, rather than static, balance [19] and that most fall-related events occur under dynamic conditions [20]. Whilst many studies point towards lower limb muscle strength and power as essential factors in control of dynamic balance [21,22], the ability to control force may also be of importance. For example, older adults with a history of falling exhibit a greater magnitude of knee extensor force variability than both age-matched non-fallers and young adults [23]. As such, it is important to extend previous findings relating force control and balance to more dynamic tasks.

The Y balance test (YBT) is a simple, valid, and reliable test of single leg dynamic balance [24]. It involves performing a series of single leg squats while attempting maximal reach with the opposite leg in the anterior, posteromedial, and posterolateral directions [24]. The distances achieved by the reaching leg reflect the dynamic control and stability of the stance leg [21]. During these reaching movements, co-contraction of the knee extensors and flexors in the stance leg is necessary to maintain stability [25]. Accordingly, knee extensor strength is a significant predictor of performance on the YBT [22,26]. To our knowledge, whether the ability to control knee extensor force is also a determinant of YBT performance (and, therefore, dynamic balance) has yet to be studied.

The aim of the present study was to extend previous findings on muscle force control and static balance in healthy adults to dynamic balance. The experimental hypotheses tested were: 1) that measures of knee extensor muscle force control (variability [CV], complexity [SampEn, DFA α]) would be correlated with performance in the YBT; and 2) that, as with static balance [15,16], measures of muscle force control would explain more variance in the performance of dynamic balance than maximal strength. This exploratory analysis is practically significant because it will provide new data that helps to better understand how the control of lower limb (specifically knee extensor) muscle force predicts performance on dynamic tasks in healthy adults.

2. Methods

2.1. Participants

Twenty-eight healthy participants (15 males, 13 females; mean ± SD: age 34.4 ± 14.8 years; height 1.72 ± 0.10 m; body mass 74.8 ± 19.2 kg) provided written informed consent to participate in the study, which was approved by the ethics committee of the University of Essex (Ref. ETH2021–0394) and which adhered to the Declaration of Helsinki. This population was chosen because exploratory research is needed to first understand biological phenomena and provide reference data from healthy individuals before turning attention to those with pathologies that affect either dynamic balance and/or muscle force control. The use of a healthy population also enables direct comparison with previous research on static balance and muscle force control [13–16]. Participants were recruited via emails distributed to university staff and students. Exclusion criteria were any recent or historical neuromuscular condition that could affect the measurements. Participants were instructed to arrive at the laboratory in a rested state (having performed no strenuous exercise in the preceding 24 h) and to have consumed neither any food nor caffeinated beverages in the 3 h prior to arrival. Participants visited the laboratory for a single session, which combined familiarisation and experimental testing.

2.2. Y balance test

On arrival at the laboratory, participants were first familiarised with, and then assessed on, the YBT [27]. The YBT apparatus consists of an elevated central footplate (2.54 cm off the ground) and pipes, with reach indicator blocks, attached in the anterior, posteromedial, and posterolateral directions. Participants were given an explanation and demonstration of the testing procedure before being invited to practice the test. As with previous studies investigating unilateral static balance and force control [16], balance was measured with the right leg as the stance leg. Participants stood with their right leg on the footplate, with the most distal aspect of their foot on a marked starting line. While maintaining single leg stance, the participants reached with their free left leg in the anterior, posteromedial, and posterolateral directions [24].

A learning effect has previously been demonstrated [28], whereby the longest reach distances occur after six attempts followed by a plateau. Accordingly, participants performed six practice trials in each of the three reach directions. They then rested for 10 min, before performing three further attempts in which the reach distance was recorded. A standardised testing order was used, with participants reaching first in the anterior, then posterolateral and finally posteromedial directions. All testing was conducted barefoot, to eliminate any additional balance and stability from the shoes [29].

2.3. Maximal strength and force control

Following completion of the YBT, participants rested for 10 min. They were then seated in the chair of a Biodex System 4 isokinetic dynamometer (Biodex Medical Systems Inc., Shirley, New York, USA), initialised and calibrated according to the manufacturer's instructions. Their right leg was attached to the lever arm of the dynamometer, with the seating position adjusted to ensure that the lateral epicondyle of the femur was in line with the axis of rotation of the lever arm. Participants sat with relative hip and knee angles of 85° and 90°, respectively, with full extension being 0°. The lower leg was securely attached to the lever arm above the malleoli with a padded Velcro strap, whilst straps secured firmly across both shoulders and the waist prevented any extraneous movement and the use of the hip extensors during the isometric contractions. The isokinetic dynamometer was connected via a custom-built cable to a CED Micro 1401–4 (Cambridge Electronic Design, Cambridge, UK). Data were sampled at 1 kHz and collected in Spike2 (Version 10; Cambridge Electronic Design, Cambridge, UK).

Participants were first familiarised with the apparatus and testing procedure by performing a series of practice isometric knee extension contractions. These contractions consisted of a series of brief (3-second) MVCs, performed until participants were able to produce 3 consecutive peak forces within 5% of each other; followed by a series of targeted (6-second) contractions at 10%, 20% and 40% of their MVC. Following these, participants rested for 10 min, before performing the experimental contractions from which measures of muscle strength and force control were recorded.

For the experimental contractions, participants first performed a series of three 3-second MVCs, each separated by 60-seconds rest. They were given a countdown, followed by very strong verbal encouragement to maximise their effort. 10 min after the establishment of maximal strength participants performed a series of targeted contractions at 10%, 20% and 40% of their MVC to assess their ability to control submaximal force. The targets were determined from the highest instantaneous force obtained during the preceding MVCs. Participants performed three contractions at each intensity, with contractions held for 6-seconds and separated by 4-seconds rest. The intensities were performed in a randomised order, with 2 min rest between each intensity. Participants were instructed to match their instantaneous force with a 1 mm thick target bar superimposed on a display placed ~1 m in front of them and were required to continue matching this target for as much of the 6-second contraction as possible.

2.4. Data analysis

For the YBT, the greatest of the three trials was used for analysis of reach distance in each direction. As reach distance is significantly correlated with leg length [30], reach distance was normalised to leg length (distance in centimetres from anterior superior iliac spine to centre of ipsilateral medial malleolus). The normalised value was calculated as: (reach distance/leg length) x 100. The normalised reach distance was, therefore, expressed as a percentage.

Maximal strength was determined as the highest instantaneous force obtained during the MVCs. For the force control tasks, the mean value of the three contractions at each intensity was calculated. Values for individual contractions were calculated based on the steadiest 5 s of each contraction, with MATLAB code identifying the 5 s of each contraction with the lowest standard deviation. The magnitude of variability in each contraction was measured using the coefficient of variation (CV), which measures the amount of variability in a time-series normalised to the mean of the time-series. Multiple metrics were used to examine complexity [9]. The regularity of force output was determined using sample entropy (SampEn) [8] and the temporal fractal scaling of force was estimated using detrended fluctuation analysis (DFA) [8]. Approximate entropy was also calculated, though as shown in Pethick et al. [31], this measure did not differ from SampEn and was not included in the present analysis. The calculations of SampEn and DFA are detailed in Pethick et al. [31]. In brief, SampEn was calculated with template length, m, set at 2 and the tolerance for accepting matches, r, set at 10% of the SD of torque output, and DFA was calculated across time scales (57 boxes ranging from 1250 to 4 data points).

2.5. Statistics

All data are presented as means ± SD. Results were deemed statistically significant when $P < 0.05$. All data were tested for normality using the Shapiro-Wilk test. Correlations between performance in each direction of the YBT (anterior, posteromedial, posterolateral) and maximal strength (MVC force)/force control (CV, SampEn and DFA α during contractions at 10%, 20% and 40% MVC) were analysed using Pearson's product-moment correlation (r) or, in the case of non-normally distributed data, Spearman's rank-order correlation (ρ). Correlation coefficients were interpreted as: 0.00 – 0.10 = negligible, 0.10 – 0.39 = weak, 0.40 – 0.69 = moderate, 0.70 – 0.89 = strong and 0.90 – 1.00 = very strong [32]. Significantly correlated variables were entered into a stepwise, linear, multiple regression model to identify measures that were most strongly associated with variance in performance of the YBT [15].

3. Results

Values for normalised reach distances in the YBT, maximal strength and measures of force control during contractions at 10%, 20% and 40% MVC are presented in Table 1.

Table 1
Measures of normalised Y balance test performance, maximal strength and force control.

Parameter	Value
Y Balance Test	
Anterior reach (% leg length)	63.2 ± 5.7
Posteromedial reach (% leg length)	112.7 ± 10.6
Posterolateral reach (% leg length)	109.9 ± 10.6
MVC (N·m)	224.0 ± 76.1
CV	
10% MVC (%)	3.56 ± 1.30
20% MVC (%)	2.81 ± 1.15
40% MVC (%)	2.88 ± 1.48
SampEn	
10% MVC	0.77 ± 0.09
20% MVC	0.67 ± 0.12
40% MVC	0.49 ± 0.11
DFA α	
10% MVC	1.04 ± 0.09
20% MVC	1.16 ± 0.09
40% MVC	1.30 ± 0.07

MVC = maximal voluntary contraction; CV = coefficient of variation; SampEn = sample entropy; DFA = detrended fluctuation analysis.

3.1. Associations between Y balance test performance and maximal strength/force control

Correlations between YBT performance and maximal strength/force control are presented in Table 2. There were no significant correlations between YBT performance in the anterior and posterolateral directions and maximal strength (both $P > 0.05$). There was, however, a significant positive correlation between YBT performance in the posteromedial direction and maximal strength ($r = 0.39$, $P = 0.043$; Fig. 2A).

There were no significant correlations between YBT performance in any of the reach directions and measures of force control (CV, SampEn, DFA α) during contractions at either 10 or 20% MVC (all $P > 0.05$). There were, however, significant moderate negative correlations between anterior reach and CV ($r = -0.44$, $P = 0.02$; Fig. 1A) and posteromedial reach and CV ($r = -0.51$, $P = 0.006$; Fig. 2B), but not posterolateral reach and CV ($P > 0.05$) during contractions at 40% MVC. There was also a significant moderate positive correlation between anterior reach and SampEn ($r = 0.47$, $P = 0.012$; Fig. 1B) during contractions at 40% MVC. There were no significant correlations between YBT performance in the posteromedial or posterolateral directions and SampEn during contractions at 40% MVC, nor were there any significant correlations between YBT performance in any of the reach directions and DFA α during contractions at 40% MVC.

Table 2
Correlations between Y balance test performance and maximal strength/force control.

Knee extensor force measure	Y Balance test reach direction		
	Anterior	Posteromedial	Posterolateral
MVC	0.03	**0.39**	*0.27*
CV			
10% MVC	–0.12	0.34	*0.17*
20% MVC	–0.13	–0.31	*–0.23*
40% MVC	**–0.44**	**–0.51**	*–0.36*
SampEn			
10% MVC	0.08	–0.02	*–0.11*
20% MVC	0.11	–0.12	*–0.12*
40% MVC	**0.47**	0.28	0.21
DFA α			
10% MVC	0.19	0.11	*0.09*
20% MVC	–0.02	0.19	*0.15*
40% MVC	–0.09	–0.15	*–0.16*

MVC = maximal voluntary contraction; CV = coefficient of variation; SampEn = sample entropy; DFA = detrended fluctuation analysis. Bold indicates significant correlation ($P < 0.05$). Italics indicates Spearman's rank order correlation.

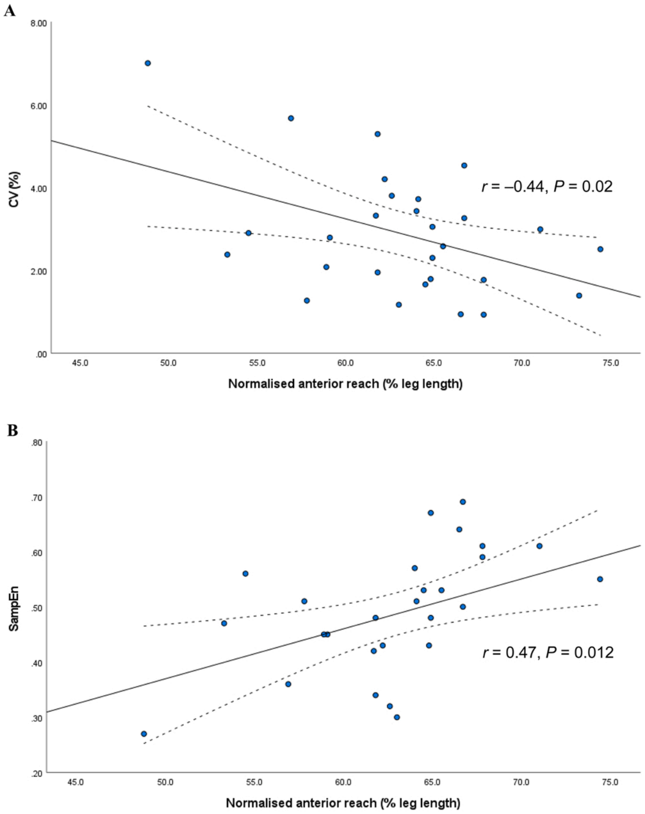

Fig. 1. Significant correlations that contributed to the regression model for YBT anterior reach. (A) correlation between YBT test anterior reach and muscle force CV during contractions at 40% MVC. (B) correlation between YBT anterior reach and muscle force SampEn during contractions at 40% MVC. Dashed lines represent 95% confidence intervals of the regression.

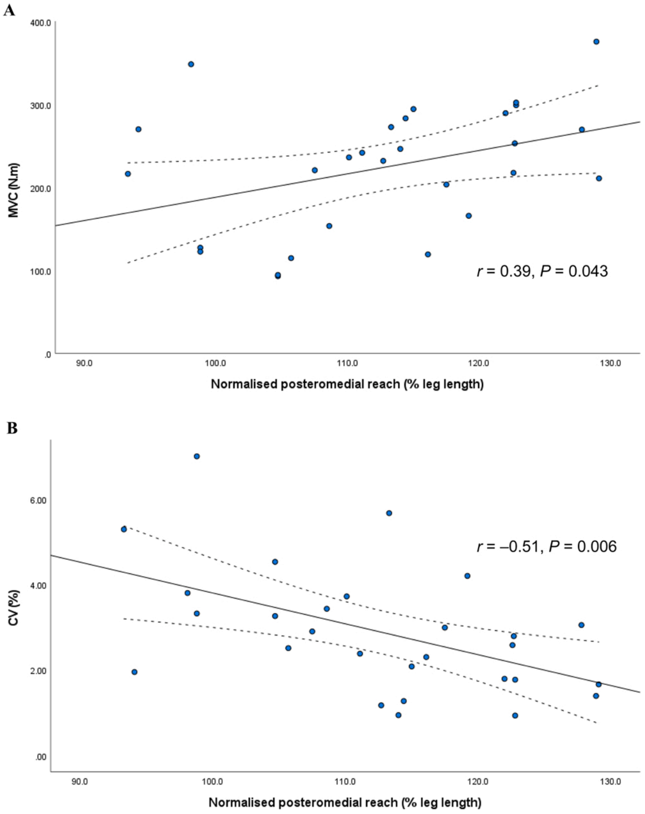

Fig. 2. Significant correlations that contributed to the regression model for YBT posteromedial reach. (A) correlation between YBT posteromedial reach and MVC. (B) correlation between YBT posteromedial reach and muscle force CV during contractions at 40% MVC. Dashed lines represent 95% confidence intervals of the regression.

3.2. Regression models to predict Y balance test performance

Based on the significant correlations observed (Table 2), stepwise, linear, multiple regression analysis was used to construct models that explained significant amounts of variance in anterior reach and posteromedial reach in the YBT. The significant correlations for anterior reach (CV and SampEn at 40% MVC) that contributed to this regression analysis are presented in Fig. 1, while the significant correlations for posteromedial reach (MVC, CV at 40% MVC) are presented in Fig. 2. The regression model for anterior reach in the YBT significantly explained ($F = 5.15$, $P = 0.013$) 54.0% of the variance in performance with two predictor variables: CV (partial $r = –0.31$) and SampEn (partial $r = 0.35$) during contractions at 40% MVC. The regression model for posteromedial reach in the YBT significantly explained ($F = 5.13$, $P = 0.014$) 53.9% of the variance wit two predictor variables: MVC (partial $r = 0.22$) and CV during contractions at 40% MVC (partial $r = –0.41$).

4. Discussion

The major novel finding of the present study was that significant correlations were observed between measures of knee extensor force control (CV and SampEn) during contractions at 40% MVC and performance in the YBT. These correlations were evident for anterior and posteromedial reach, but not posterolateral reach, thus providing only partial support for our first hypothesis. Nevertheless, regression analysis demonstrated that knee extensor force CV and SampEn during contractions at 40% MVC predicted a moderate amount of performance in YBT anterior reach and, therefore, in dynamic balance. Similarly, knee extensor MVC and force CV during contractions at 40% MVC predicted a moderate amount of performance in YBT posteromedial reach. Measures of force control were, therefore, a more consistent predictor of YBT performance than maximal strength, in accord with our second hypothesis.

It has been demonstrated that lower muscle force CV (i.e., greater steadiness) is associated with smaller centre of pressure displacements (i.e., less postural sway) in healthy adults [13,15,16]. The moderate negative correlations observed between knee extensor force CV and YBT performance in the present study (Table 2, Figs. 1A and 2B) indicate that lower CV is associated with greater anterior and posteromedial reach in the YBT. The positive correlation observed between knee extensor force SampEn and YBT performance (Table 2, Fig. 1B) indicates that greater SampEn is associated with greater anterior reach. Based on the purported significance of muscle force CV and SampEn [3] and the YBT [21], these results indicate that greater force steadiness and adaptability are associated with greater dynamic control and stability in healthy adults. The maximal strength of the knee extensors only exhibited a significant correlation with YBT performance in the posteromedial direction and was, therefore, a less consistent predictor of performance than force control measures.

These results add to the growing body of literature demonstrating that muscle force CV during submaximal isometric contractions is predictive of performance during functional tasks in healthy adults [1]. This study is the first to extend previous findings relating muscle force CV and static balance in healthy adults [13,15,16] to dynamic balance in healthy adults. Importantly, it is also the first study to empirically demonstrate a relationship between complexity-based measures of muscle force control (SampEn) and functional performance. It has been argued that a lack of empirical evidence relating muscle force complexity to functional performance has limited the uptake of complexity-based measures in research [3]. The present findings indicate that muscle force SampEn is an important explanatory variable for YBT and dynamic balance performance. Moreover, muscle force SampEn exhibited a similarly strong correlation with YBT anterior reach as muscle force CV (Table 2). These results provide further justification that both magnitude- and complexity-based measures should be used to characterise force control and its relationship with functional performance.

The presently observed relationship between muscle force complexity and dynamic balance provides a parallel with the complexity of other physiological outputs, which have been demonstrated to have empirical relationships with functional performance. Most relevantly, low complexity in postural sway during quiet stance (measured using multiscale entropy) has been demonstrated to predict increased postural sway speed during tasks of increasing difficulty [33]. Thus, it appears that complexity in various neuromuscular outputs is important for the adaptive capacity of the postural control system.

An implication of these results is that, in theory, improving muscle force control (i.e., decreasing CV and increasing SampEn) during moderate intensity (~40% MVC) contractions should result in a predictable increase in performance of the YBT and, accordingly, an improvement in dynamic balance. When force control training has been tested with regards to static balance, however, conflicting results have arisen. Oshita & Yano [38] initially demonstrated that 4 weeks of low-intensity (10% and 20% MVC) plantarflexor force steadiness training decreased both plantarflexor force SD and postural sway centre of pressure displacements during quiet standing in young adults. Conversely, Barbosa et al. [39] recently found a training-induced decrease in plantarflexor force SD was associated with worsened postural sway in older adults. Such results emphasise that there are considerable gaps in our knowledge of the explanatory power of force control measures for performance of functional activities and suggest that the relationship between force control and functional activities may depend on the age of the population studied. Further research on the optimal training protocol (i.e., type, intensity and dose of training) to increase force control and static and dynamic components of balance is undoubtedly warranted. Research on gait variability has demonstrated that force control training involving tracking a sinusoidal output is a promising approach to improving both force control and functional performance [40].

4.1. Limitations

The correlations between dynamic balance and knee extensor force control were evident at a higher contraction intensity (40% MVC) than those previously reported for static balance and ankle plantarflexor, ankle dorsiflexor and hip abductor force control (typically $\leq$5% MVC) [13,15,16]. This is not surprising, as the force requirement for static and dynamic balance tasks differs considerably. It has been demonstrated that EMG activity in the ankle plantarflexors, ankle dorsiflexors and hip abductors during static balance tasks is typically $\leq$ 15% of that obtained during a maximal isometric contraction [34,35]. In contrast, knee extensor EMG activity during anterior reach in the YBT can reach up to 70% of that obtained during a maximal isometric contraction [36]. It is, therefore, possible that force control at higher contraction intensities than those used in the present study would exhibit stronger correlations with YBT performance and explain a greater amount of variance in performance. As such, it could be argued that a limitation of the present study was its failure to examine force control during the higher intensity contractions characteristic of the YBT.

Similarly, that the regression model only explained a moderate amount of variance in anterior and posteromedial reach and that no significant associations were observed for posterolateral reach (Table 2) could also be considered a limitation. It has previously been demonstrated that vastus medialis EMG activity is greater during reach in the anterior direction compared to the posteromedial and posterolateral directions [25]. Moreover, muscles such as the biceps femoris, tibialis anterior, gluteus maximus and gluteus medius [25,37] all exhibit greater activation during reach in the posteromedial and posterolateral directions than in the anterior direction. Such observations could account for the results in the present study and indicate that more of the variance in all three reach directions could have been explained if we had also investigated force control in the other muscle groups that contribute to YBT performance. A further limitation of the study was the relatively small sample size (n = 28), though this was comparable with previous studies utilising similar regression analyses to investigate the relationship between measures of force control and performance of tests of motor function [11,12].

5. Conclusion

Our findings are the first to indicate that a moderate amount of variance in dynamic balance in healthy adults can be explained by measures of knee extensor force control obtained from isometric contractions. Importantly, both knee extensor force CV and SampEn contributed to the variance in dynamic balance, emphasising the need for future studies investigating the relationship between force control and functional performance to consider both magnitude- and complexity-based measures of force control. The fact that knee extensor force control could only explain a moderate amount of variance in dynamic balance performance in healthy adults indicates that force control in other muscle groups that contribute significantly to dynamic balance should also be considered in future studies.

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CRediT authorship contribution statement

Emily Mear: Funding acquisition, Investigation, Methodology, Writing – review & editing. **Valerie Gladwell:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review & editing. **Jamie Pethick:** Conceptualization, Investigation, Methodology, Formal analysis, Supervision, Writing – original draft, Writing – review & editing.

Declaration of interest

None.

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