**Knee extensor force control as a predictor of dynamic balance**

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**Abstract**

Previous research has demonstrated that muscle force control in various muscle of the lower limb (measured according to the magnitude of force fluctuations) explains a significant amount of variance in static balance. To determine whether muscle force control also explains significant variance in dynamic balance, Y balance test performance and knee extensor muscle force control were measured in 20 healthy participants. The Y balance test 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 of force fluctuations, using the coefficient of variation (CV), and according to the temporal structure of force fluctuations, using approximate entropy (ApEn) and detrended fluctuation analysis α. A significant negative correlation was observed for Y balance test anterior reach and muscle force CV during contractions at 40% MVC (*r* = –0.44, *P* = 0.05) and a significant positive correlation observed for anterior reach and muscle force ApEn during contractions at 40% MVC (*r* = 0.53, *P* = 0.015). A subsequent regression model demonstrated that muscle force CV and ApEn during contractions at 40% MVC significantly explained 32.3% of variance in Y balance test anterior reach. 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.

**Introduction**

The production of voluntary force (and, therefore, movement) is accomplished through the precise activation of motor unit populations (Enoka and Farina, 2021). 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 (Enoka *et al*., 2003). These fluctuations can be quantified using magnitude- or complexity-based measures, with each providing unique insight into the ability to control muscle force output (Nagamori *et al*., 2021; Pethick *et al*., 2021). 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 (Slifkin and Newell, 1999) and provide an index of force steadiness. Importantly, the CV (i.e. the 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 (Negro *et al*., 2009; Farina and Negro, 2015). Complexity-based measures quantify the degree of time-series irregularity (e.g. approximate entropy, ApEn; Pincus, 1991) and identify the presence of long-rage fractal correlations (e.g. detrended fluctuation analysis α, DFA; Peng *et al*., 1994); properties which magnitude-based measures cannot quantify (Goldberger *et al*., 2002). Complexity-based measures provide an index of adaptability; that is, the ability to modulate force output rapidly and accurately in response to task demands (Vaillancourt and Newell, 2003; Pethick *et al*., 2016). It has been recommended that the use of both magnitude- and complexity-based measures is necessary for a thorough examination of muscle force control (Goldberger *et al*., 2002; Pethick *et al*., 2021).

The fluctuations evident in muscular output are of functional significance, influencing our ability to achieve a desired force and produce an intended movement trajectory (Enoka *et al*., 2003). 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; Almuklass *et al*., 2016; Feeney *et al*., 2018), walking (plantarflexors; Mani *et al*., 2018) and static balance (plantarflexors; Kouzaki and Shinohara, 2010; Oshito and Yano, 2010). Moreover, several studies on static balance have found the CV of force fluctuations in the hip abductors and ankle dorsiflexors (Davis *et al*., 2020a) and ankle plantarflexors (Hirono *et al*., 2020) 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 (Davis *et al*., 2020a).

Balance control is, however, a complex phenomenon that is not amenable to characterisation by a single test (Winter *et al*., 1990). 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 (Winter *et al*., 1990). Given the dynamic nature of many activities of daily living and of most sports, assessment of balance and its determinants under such dynamic conditions is of critical importance (Ringhof and Stein, 2018). This is illustrated by the observation that risk of falling is more closely related to dynamic, rather than static, balance (Rubenstein, 2006) and that most fall-related events occur under dynamic conditions (Blake *et al*., 1988). Whilst many studies point towards lower limb muscle strength and power as essential factors in control of dynamic balance (Carter *et al*., 2002; Lockie *et al*., 2013; Booysen *et al*., 2015), evidence suggests that the ability to control force may also be of importance. For example, it has been demonstrated that 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 (Carville *et al*., 2007). As such, it is important to extend previous findings relating force control and balance to more dynamic tasks.

The Y balance test is a simple, valid, and reliable test of single leg dynamic balance (Plisky *et al*., 2009;Sipe *et al*., 2019). It involves performing a series of single leg squats while attempting maximal reach with the opposite leg in the anterior, posteromedial, and posterolateral directions (Plisky *et al*., 2009). The distances achieved by the reaching leg reflect the dynamic control and stability of the stance leg (Lockie *et al*., 2013). During these reaching movements, co-contraction of the knee extensors and flexors in the stance leg is necessary to maintain stability (Earl and Hertel, 2001). Accordingly, knee extensor strength is a significant predictor of performance on the Y balance test (Booysen *et al*., 2015; Guirelli *et al*., 2021). To our knowledge, whether the ability to control knee extensor force is also a determinant of Y balance test 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 to dynamic balance (i.e. the Y balance test). The experimental hypotheses tested were: 1) that measures of knee extensor muscle force control (variability [CV], complexity [ApEn, DFA α]) would be correlated with performance in the Y balance test; and 2) that, as with static balance (Davis *et al*., 2020a; Hirono *et al*., 2021), measures of muscle force control would explain more variance in the performance of dynamic balance than maximal strength.

**Methods**

*Participants*

20 healthy participants (9 males, 11 females; mean ± SD: age 31.6 ± 12.9 years; height 1.72 ± 0.09 m; body mass 76.7 ± 21.3 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. Participants were instructed to arrive at the laboratory in a rested state (having performed no strenuous exercise in the preceding 24 hours) and to have consumed neither any food nor caffeinated beverages in the 3 hours prior to arrival. Participants visited the laboratory for a single session, which combined familiarisation and experimental testing.

*Y balance test*

On arrival at the laboratory, participants were first familiarised with, and then assessed on, the Y balance test (Plisky *et al*., 2006). The Y balance test 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 (Hirono *et al*., 2020), 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 (Plisky *et al*., 2009).

A significant learning effect has previously been demonstrated (Hertel *et al*., 2000), whereby the longest reach distances occur after six attempts followed by a plateau. As such, participants performed six practice trials in each of the three reach directions. They then rested for 10 minutes, 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 (Coughlan *et al*., 2012).

*Maximal strength and force control*

Following completion of the Y balance test, participants rested for 10 minutes. 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 maximal and submaximal isometric knee extension contractions. These practice 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 minutes, 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 minutes 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 minutes rest between each intensity. Participants were instructed to match their instantaneous force with a 1mm thick target bar superimposed on a display placed ~1m in front of them and were required to continue matching this target for as much of the 6-second contraction as possible.

*Data analysis*

For the Y balance test, 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 (Gribble and Hertel, 2003), 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 seconds of each contraction, with MATLAB code identifying the 5 seconds of each contraction with the lowest standard deviation (SD). The magnitude of variability in each contraction was measured using the coefficient of variation (CV), which provides a measure of the amount of variability in a time-series normalised to the mean of the time-series. As recommended by Goldberger *et al*. (2002), multiple metrics were used to examine complexity. The regularity of force output was determined using approximate entropy (ApEn; Pincus, 1991) and the temporal fractal scaling of force was estimated using detrended fluctuation analysis (DFA; Peng *et al*., 1994). Sample entropy was also calculated, though as shown in Pethick *et al*. (2015), this measure does not differ from ApEn when 5,000 data points are used in its calculation. The calculations of ApEn and DFA are detailed in Pethick *et al*. (2015). In brief, ApEn 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).

*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 Y balance test (anterior, posteromedial, posterolateral) and maximal strength (MVC force)/force control (CV, ApEn 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*). 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 Y balance test (Davis *et al*., 2020a; Davis *et al*., 2020b).

**Results**

Values for normalised reach distance (anterior, posteromedial, and posterolateral directions) in the Y balance test, maximal strength and measures of force control (CV, ApEn, DFA α) during contractions at 10, 20 and 40% MVC are presented in Table 1.

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

Correlations between Y balance test performance and maximal strength/force control are presented in Table 2. There were no significant correlations between Y balance test performance in any of the reach directions (anterior, posteromedial, or posterolateral) and maximal strength (all *P* > 0.05). There were no significant correlations between Y balance test performance in any of the reach directions and measures of force control (CV, ApEn, DFA α) during contractions at either 10 or 20% MVC (all *P* > 0.05). There was, however, a significant negative correlation between anterior reach and CV (*r* = –0.44, *P* = 0.05; Figure 1A) and a significant positive correlation between anterior reach and ApEn (*r* = 0.53, *P* = 0.015; Figure 1B) during contractions at 40% MVC. There were no significant correlations between Y balance test performance in the posteromedial or posterolateral directions and either CV or ApEn during contractions at 40% MVC, nor were there any significant correlations between Y balance test performance in any of the reach directions and DFA α during contractions at 40% MVC.

*Regression models*

Based on the correlations observed between anterior reach and force control during contractions at 40% MVC (Table 2), a stepwise, linear, multiple regression analysis was used to construct a model that explained significant amounts of variance in anterior reach in the Y balance test. The significant correlations (anterior reach and CV at 40% MVC, anterior reach and ApEn at 40% MVC) that contributed to this regression analysis are presented in Figure 1. The regression model for anterior reach in the Y balance test significantly explained (*F* = 4.07, *P* = 0.036) 32.3% of the variance in performance with two predictor variables: CV (partial *r* = –0.24) and ApEn (partial *r* = 0.40) during contractions at 40% MVC.

**Discussion**

The major novel finding of the present study was that significant correlations were observed between measures of knee extensor force control (CV and ApEn) during contractions at 40% MVC and performance in the Y balance test. These correlations were, however, only evident for anterior reach in the Y balance test and not for either posteromedial or posterolateral reach, thus providing only partial support for our first hypothesis. Nevertheless, regression analysis demonstrated that knee extensor force CV and ApEn during contractions at 40% MVC predicted a moderate amount of performance in Y balance test anterior reach and, therefore, in dynamic balance. Consistent with our second hypothesis, measures of knee extensor force control explained more variance in Y balance test performance than maximal strength.

It has been repeatedly demonstrated that lower muscle force CV (i.e. greater steadiness) is associated with smaller centre of pressure displacements (i.e. less postural sway; Kouzaki and Shinohara, 2010; Davis *et al*., 2020a; Hirono *et al*., 2020). The negative correlation observed between knee extensor force CV and Y balance test performance in the present study (Table 2, Figure 1a) indicates that lower CV is associated with greater anterior reach. The positive correlation observed between knee extensor force ApEn and Y balance test performance (Table 2, Figure 1b) indicates the greater ApEn is associated with greater anterior reach. These two force control measures combined to explain a moderate amount of variance (32.3%) in anterior reach. Based on the purported significance of muscle force CV and ApEn (Pethick *et al*., 2021) and the Y balance test (Lockie *et al*., 2013), these results indicate that greater force steadiness and adaptability are associated with greater dynamic control and stability. In contrast to previous studies (Guirelli *et al*., 2021), the maximal strength of the knee extensors did not exhibit a significant correlation with Y balance test performance and, consequently, did not contribute to the regression analysis.

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 (Enoka and Farina, 2021). Furthermore, this study is the first to extend previous findings relating muscle force CV and static balance (Shinohara and Kouzaki, 2010; Davis *et al*., 2020a; Hirono *et al*., 2020) to dynamic balance. Importantly, it is also the first study to empirically demonstrate a relationship between complexity-based measures of muscle force control (ApEn) and functional performance. It has previously been argued that this lack of empirical evidence relating muscle force complexity to functional performance has limited the uptake of complexity-based measures in research (Pethick *et al*., 2021). The present findings indicate that muscle force ApEn is an important explanatory variable for Y balance test and, therefore, dynamic balance performance. Moreover, muscle force ApEn exhibited a stronger correlation with Y balance test anterior reach than muscle force CV (Table 2). These results provide further justification that both magnitude- and complexity-based measures should be used to characterise not only force control but also its association 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 (Manor *et al*., 2010). Thus, it appears that complexity in various neuromuscular outputs is important for the adaptive capacity of the postural control system.

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 ≤5% MVC; Kouzaki and Shinohara, 2010; Davis *et al*., 2020a; Hirono *et al*., 2020). 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 (soleus), ankle dorsiflexors (tibialis anterior) and hip abductors (gluteals) during static balance tasks is typically ≤15% of the value obtained during a maximal isometric contraction (Florence Tse *et al*., 2013; Sozzi *et al*., 2013). In contrast, knee extensor (vastus medialis) EMG activity during anterior reach in the Y balance test can reach up to 70% of the value obtained during a maximal isometric contraction (Norris and Trudelle-Jackson, 2011). It is, therefore, possible that force control at higher contraction intensities than those used in the present study would exhibit stronger correlations with Y balance test 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 Y balance test.

A further limitation of the study was the observation that the regression model only explained a moderate amount of variance in anterior reach and that no significant associations were observed for posteromedial or posterolateral reach (Table 2). 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 (Earl and Hertel, 2001). Moreover, muscles such as the biceps femoris (Earl and Hertel, 2001), tibialis anterior, gluteus maximus and gluteus medius (Jaber *et al*., 2018) all exhibit greater activation during reach in the posteromedial and posterolateral directions than in the anterior direction. These observations could potentially account for the results in the present study and indicate that perhaps more of the variance in reach distance (in all three directions) could have been explained if we had also investigated force control in the other muscle groups that contribute to Y balance test performance. Furthermore, as both magnitude- and complexity-based measures of force control depend on the discharge characteristics of activated motor units (Farina and Negro, 2015; Dideriksen *et al*., 2021), these should also be measured and related to Y balance test performance.

An implication of these results is that, in theory, improving muscle force control (i.e. decreasing CV and increasing ApEn) should result in a predictable increase in anterior reach distance and, accordingly, an improvement in dynamic balance. Any such improvement would likely have a concomitant effect on decreasing risk of falls. When force control training has been tested with regards to static balance, however, conflicting results have arisen. Oshita and Yano (2011) 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*. (2020) 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 still considerable gaps in our knowledge of the explanatory power of force control measures for performance of functional activities (Enoka and Farina, 2021) 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 (Patel *et al*., 2021).

*Conclusion*

In summary, our findings are the first to indicate that a moderate amount of variance in dynamic balance can be explained by measures of knee extensor force control obtained from isometric contractions. Importantly, both knee extensor force CV and ApEn contributed to the variance in dynamic balance. This emphasises 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 performance indicates that force control in other muscle groups that contribute significantly to dynamic balance should also be considered in future studies.

**References**

Almuklass, A.M., Price, R.C., Gould, J.R. and Enoka, R.M. (2016). Force steadiness as a predictor of time to complete a pegboard test of dexterity in young men and women. *Journal of Applied Physiology,* **120,** 1410-1417. <https://doi.org/10.1152/japplphysiol.01051.2015>

Barbosa, R.N., Silva, N.R., Santos, D.P., Moraes, R. and Gomes, M.M. (2020). Force stability training decreased force variability of plantar flexor muscles without reducing postural sway in female older adults. *Gait & Posture,* **77,** 288-292. <https://doi.org/10.1016/j.gaitpost.2020.02.015>

Blake, A.J., Morgan, K., Bendall, M.J., Dallosso, H., Ebrahim, S.B.J., Arie, T.A., Fentem, P.H. and Bassey, E.J. (1988). Falls by elderly people at home: prevalence and associated factors. *Age and Ageing,* **17,** 365-372. <https://doi.org/10.1093/ageing/17.6.365>

Booysen, M.J., Gradidge, P.J.L. and Watson, E. (2015). The relationships of eccentric strength and power with dynamic balance in male footballers. *Journal of Sports Sciences,* **33,** 2157-2165. <https://doi.org/10.1080/02640414.2015.1064152>

Carter, N.D., Khan, K.M., Mallinson, A., Janssen, P.A., Heinonen, A., Petit, M.A. and McKay, H.A. (2002). Knee extension strength is a significant determinant of static and dynamic balance as well as quality of life in older community-dwelling women with osteoporosis. *Gerontology,* **48,** 360-368. <https://doi.org/10.1159/000065504>

Carville, S.F., Perry, M.C., Rutherford, O.M., Smith, I.C.H. and Newham, D.J. (2007). Steadiness of quadriceps contractions in young and older adults with and without a history of falling. *European Journal of Applied Physiology,* **100,** 527-533. <https://doi.org/10.1007/s00421-006-0245-2>

Coughlan, G.T., Fullam, K., Delahunt, E., Gissane, C. and Caulfield, B.M. (2012). A comparison between performance on selected direction of the Star Excursion Balance Test and the Y Balance Test. *Journal of Athletic Training,* **47,** 366-371. <https://doi.org/10.4085/1062-6050-47.4.03>

Davis, L.A., Allen, S.P., Hamilton, L.D., Grabowski, A.M. and Enoka, R.M. (2020a). Differences in postural sway among healthy adults are associated with the ability to perform steady contractions with leg muscles. *Experimental Brain Research,* **238,** 487-497. <https://doi.org/10.1007/s00221-019-05719-4>

Davis, L.A., Alenazy, M.S., Almuklass, A.M., Feeney, D.F., Vieira, T., Botter, A. and Enoka, R. (2020b). Force control during submaximal isometric contractions is associated with walking performance in persons with multiple sclerosis. *Journal of Neurophysiology,* **123,** 2191-2200. <https://doi.org/10.1152/jn.00085.2020>

Dideriksen, J., Elias, L.A., Zambalde, E.P., Germer, C.M., Molinaro, R.G. and Negro, F. (2021). Influence of central and peripheral motor unit properties on isometric muscle force entropy: a computer simulation study. *Journal of Biomechanics,* 110886. <https://doi.org/10.1016/j.jbiomech.2021.110866>

Earl, J.E. and Hertel, J. (2001). Lower-extremity muscle activation during the Star Excursion Balance Tests. *Journal of Sport Rehabilitation,* **10,** 93-104. <https://doi.org/10.1123/jsr.10.2.93>

Enoka, R.M., Christou, E.A., Hunter, S.K., Kornatz, K.W., Semmler, J.G., Taylor, A.M. and Tracy, B.L. (2003). Mechanisms that contribute to differences in motor performance between young and old adults. *Journal of Electromyography & Kinesiology,* **13,** 1-12. [https://doi.org/10.1016/S1050-6411(02)00084-6](https://doi.org/10.1016/S1050-6411%2802%2900084-6)

Enoka, R.M. and Farina, D. (2021). Force steadiness: from motor units to voluntary actions. *Physiology,* **36,** 114-130. <https://doi.org/10.1152/physiol.00027.2020>

Farina, D. and Negro, F. (2015). Common synaptic input to motor neurons, motor unit synchronization, and force control. *Exercise and Sport Sciences Reviews,* **43,** 23-33. <http://doi.org/10.1249/JES.0000000000000032>

Feeney, D.F., Mani, D. and Enoka, R.M. (2018). Variability in common synaptic input to motor neurons modulates both force steadiness and pegboard time in young and older adults. *Journal of Physiology,* **596,** 3793-3806. <https://doi.org/10.1113/JP275658>

Florence Tse, Y.Y., Petrofsky, J., Berk, L., Daher, N., Lohman, E., Cavalcanti, P., Laymon, M., Rodrigues, S., Lodha, R. and Potnis, P.A. (2013). Postural sway and EMG analysis of hip and ankle muscles during balance tasks. *International Journal of Therapy and Rehabilitation,* **20,** 280-288. <https://doi.org/10.12968/ijtr.2013.20.6.280>

Goldberger, A.L., Amaral, L.A., Hausdorff, J.M., Ivanov, P.C., Peng, C.K. and Stanley, H.E. (2002). Fractal dynamics in physiology: alterations with disease and aging. *Proceedings of the National Academy of Sciences,* **99,** 2466-2472. <https://doi.org/10.1073/pnas.012579499>

Gribble, P.A. and Hertel, J. (2003). Considerations for normalizing measures of the Star Excursion Balance Test. *Measurement in Physical Education and Exercise Science,* **7,** 89-100. <https://doi.org/10.1207/S15327841MPEE0702_3>

Guirelli, A.R., Carvalho, C.A., Dos Santos, J.M. and Felicio, L.R. (2021). Relationship between the strength of the hip and knee stabilizer muscles and the Y balance test performance in adolescent volleyball athletes. *The Journal of Sports Medicine and Physical Fitness,* **61,** 1326-1332. http://doi.org.uk/[10.23736/s0022-4707.21.11744-x](https://doi.org/10.23736/s0022-4707.21.11744-x)

Hertel, J., Miller, S. and Denegar, C. (2000). Intratester and intertester reliability during the Star Excursion Balance Test. *Journal of Sport Rehabilitation,* **9,** 104-116. <https://doi.org/10.1123/jsr.9.2.104>

Hirono, T., Ikezoe, T., Yamagata, M., Kato, T., Kimura, M. and Ichihashi, N. (2021). Relationship between ankle plantar flexor force steadiness and postural stability on stable and unstable platforms. *European Journal of Applied Physiology,* **120,** 1075-1082. http://doi.org/[10.1007/s00421-020-04346-0](https://doi.org/10.1007/s00421-020-04346-0)

Jaber, H., Lohman, E., Daher, N., Bains, G., Nagaraj, A., Mayekar, P., Shanbhag, M. and Alameri, M. (2018). Neuromuscular control of ankle and hip during performance of the star excursion balance test in subjects with and without chronic ankle instability. *PloS One,* **13,** e0201479. <https://doi.org/10.1371/journal.pone.0201479>

Kouazaki, M. and Shinohara, M. (2010). Steadiness in plantar flexor muscles and its relation to postural sway in young and elderly adults. *Muscle & Nerve,* **42,** 78-87. <https://doi.org/10.1002/mus.21599>

Lockie, R.G., Schultz, A.B., Callaghan, S.J. and Jeffriess, M.D. (2013). The effects of isokinetic knee extensor and flexor strength on dynamic stability as measured by functional reaching. *Isokinetics and Exercise Science,* **21,** 301-309. <http://doi.org/10.3233/IES-130501>

Mani, D., Almuklass, A.M., Hamilton, L.D., Vieira, T.M., Botter, A. and Enoka, R.M. (2018). Motor unit activity, force steadiness, and perceived fatigability are correlated with mobility in older adults. *Journal of Neurophysiology,* **120,** 1988-1997. <https://doi.org/10.1152/jn.00192.2018>

Nagamori, A., Laine, C.M., Loeb, G.E. and Valero-Cuevas, F.J. (2021). Force variability is mostly not motor noise: Theoretical implications for motor control. PLoS Computational Biology, **17,** e1008707. <https://doi.org/10.1371/journal.pcbi.1008707>

Negro, F., Holobar, A. and Farina, D. (2009). Fluctuations in isometric muscle force can be described by one linear projection of low-frequency components of motor unit discharge rates. *Journal of Physiology,* **587,** 5925-5938. <https://doi.org/10.1113/jphysiol.2009.178509>

Norris, B. and Trudelle-Jackson, E. (2011). Hip- and thigh-muscle activation during the star excursion balance test. *Journal of Sport Rehabilitation,* **20,** 428-441. <http://doi.org/10.1123/jsr.20.4.428>

Oshita, K. and Yano, S. (2010). Relationship between force fluctuations in the plantar flexor and sustainable time for single-leg standing. *Journal of Physiological Anthropology,* **29,** 89-93. <https://doi.org/10.2114/jpa2.29.89>

Oshita, K. and Yano, S. (2011). Low-frequency force steadiness practice in plantar flexor muscle reduces postural sway during quiet standing. *Journal of Physiological Anthropology,* **30,** 233-239. <https://doi.org/10.2114/jpa2.30.233>

Patel, P., Casamento-Moran, A., Christou, E.A. and Lodha, N. (2021). Force-control vs. strength training: The effect on gait variability in stroke survivors. *Frontiers in Neurology,* **12**, 667340. <https://doi.org/10.3389/fneur.2021.667340>

Peng, C.K., Buldyrev, S.V., Havlin, S., Simons, M., Stanley, H.E. and Goldberger, A.L. (1994). Mosaic organization of DNA nucleotides. *Physical Review E,* **49,** 1685-1689. <https://doi.org/10.1103/PhysRevE.49.1685>

Pethick, J., Winter, S.L. and Burnley, M. (2015). Fatigue reduces the complexity of knee extensor torque fluctuations during maximal and submaximal intermittent isometric contractions in man. *Journal of Physiology,* **593,** 2085-2096. <https://doi.org/10.1113/jphysiol.2015.284380>

Pethick, J., Winter, S.L. and Burnley, M. (2016). Loss of knee extensor torque complexity during fatiguing isometric muscle contractions occurs exclusively above the critical torque. *American Journal of Physiology,* **310,** R1144-R1153. <https://doi.org/10.1152/ajpregu.00019.2016>

Pethick, J., Winter, S.L. and Burnley, M. (2021). Physiological complexity: influence of ageing, disease and neuromuscular fatigue on muscle force and torque fluctuations. *Experimental Physiology,* **106,** 2046-2059. <https://doi.org/10.1113/EP089711>

Pincus, S.M. (1991). Approximate entropy as a measure of system complexity. *Proceedings of the National Academy of Sciences,* **88,** 2297-2301. <https://doi.org/10.1073/pnas.88.6.2297>

Plisky, P.J., Rauh, M.J., Kaminski, T.W. and Underwood, F.B. (2006). Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *Journal of Orthopaedic & Sports Physical Therapy,* **36,** 911-919. <https://www.jospt.org/doi/10.2519/jospt.2006.2244>

Plisky, P.J., Gorman, P.P., Butler, R.J., Kiesel, K.B., Underwood, F.B. and Elkins, B. (2009). The reliability of an instrumented device for measuring components of the Star Excursion Balance Test. *North American Journal of Sports Physical Therapy,* **4,** 92-99.

Ringhof, S. and Stein, T. (2018). Biomechanical assessment of dynamic balance: specificity of different balance tests. *Human Movement Science,* **58,** 140-147. <https://doi.org/10.1016/j.humov.2018.02.004>

Rubenstein, L.Z. (2006). Falls in older people: epidemiology, risk factors and strategies for prevention. *Age and Ageing,* **35,** ii37-ii41. <https://doi.org/10.1093/ageing/afl084>

Sipe, C.L., Ramey, K.D., Plisky, P.P. and Taylor, J.D. (2019). Y-balance test: a valid and reliable assessment in older adults. *Journal of Aging and Physical Activity,* **27,** 663-669. <https://doi.org/10.1123/japa.2018-0330>

Slifkin, A.B. and Newell, K.M. (1999). Noise, information transmission, and force variability. *Journal of Experimental Psychology,* **25,** 837-851. [https://doi.org/10.1037/0096-1523.25.3.837](https://psycnet.apa.org/doi/10.1037/0096-1523.25.3.837)

Sozzi, S., Honeine, J.L., Do., M.C. and Shiepatti, M. (2013). Leg muscle activity during tandem stance and the control of body balance in the frontal place. *Clinical Neurophysiology,* **124,** 1175-1186. <https://doi.org/10.1016/j.clinph.2012.12.001>

Vaillancourt, D.E. and Newell, K.M. (2003). Aging and the time and frequency structure of force output variability. *Journal of Applied Physiology,* **94,** 903-912. <https://doi.org/10.1152/japplphysiol.00166.2002>

Winter, D.A., Patla, A.E. and Frank, J.S. (1990). Assessment of balance control in humans. *Medical Progress through Technology,* **16,** 31-51.

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



*r* = 0.53, *P* = 0.015

*r* = –0.44, *P* = 0.05

**B**

**A**

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

|  |  |
| --- | --- |
| Parameter | Value |
| Y Balance Test |  |
|  Anterior reach (% leg length) | 62.5 ± 5.9 |
|  Posteromedial reach (% leg length) | 110.7 ± 10.5 |
|  Posterolateral reach (% leg length) | 108.5 ± 10.6 |
|  |  |
| MVC (N·m) | 211.7 ± 72.1 |
|  |  |
| CV |  |
|  10% MVC (%) | 4.16 ± 0.91 |
|  20% MVC (%) | 3.27 ± 0.97 |
|  40% MVC (%) | 3.40 ± 1.37 |
|  |  |
| ApEn |  |
|  10% MVC | 0.82 ± 0.10 |
|  20% MVC | 0.74 ± 0.12 |
|  40% MVC | 0.56 ± 0.13 |
|  |  |
| DFA α |  |
|  10% MVC | 1.02 ± 0.08 |
|  20% MVC | 1.15 ± 0.08 |
|  40% MVC | 1.29 ± 0.07 |

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

**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 | –0.12 | –0.23 | *–0.16* |
|  |  |  |  |
| CV |  |  |  |
|  10% MVC | 0.08 | –0.05 | –0.05 |
|  20% MVC | –0.14 | –0.04 | *–0.23* |
|  40% MVC | **–0.44** | –0.42 | –0.30 |
|  |  |  |  |
| ApEn |  |  |  |
|  10% MVC | –0.08 | –0.11 | –0.15 |
|  20% MVC | –0.007 | –0.16 | *–0.20* |
|  40% MVC | **0.53** | 0.34 | 0.18 |
|  |  |  |  |
| DFA α |  |  |  |
|  10% MVC | 0.27 | –0.03 | –0.06 |
|  20% MVC | 0.09 | 0.23 | *0.40* |
|  40% MVC | –0.15 | –0.29 | –0.27 |

MVC = maximal voluntary contraction; CV = coefficient of variation; ApEn = approximate entropy; DFA = detrended fluctuation analysis. **Bold** indicates significant correlation (*P* < 0.05). *Italics* indicates Spearman’s rank order correlation.