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Muscular coordination during vertical jumping

Authors' Contribution:
A Study Design
B Data Collection
C Statistical Analysis
D Data Interpretation
E Manuscript Preparation
F Literature Search
G Funds Collection

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abstract

Background: The musculoskeletal system has a relatively large number of mechanical degrees of freedom. In order to permit coordinated movement, it is thought that these degrees of freedom are constrained, reducing the complexity of the motor control problem. For this reason, principal component analysis can be a powerful technique for understanding the organisation of movement by calculating the number of functional degrees of freedom present in a particular movement task.

Material and methods: In this study, we used principal component analysis to find the number of functional degrees of freedom exhibited during vertical jumping. We applied the technique to both the inter-segmental moments and the muscle forces (that were estimated based upon a publicly available musculoskeletal model of the lower limb).

Results: We found that over 90% of the variance in the 3 dimensional inter-segmental moments could be described by 3 principal components (PC1 = 61.0%, PC2 = 15.8%, PC3 = 13.4%), suggesting the presence of 3 functional degrees of freedom. Similarly, only 4 principal components (PC1 = 50.1%, PC2 = 22.5%, PC3 = 13.5%, PC4 = 4.8%) were required to capture 90% of the variance in muscle forces.

Conclusions: These results suggest that there is a marked inter-individual similarity in both moments and muscle forces during vertical jumping.

Key words: principal component analysis, degrees of freedom, muscle force, proximal to distal, FreeBody, musculoskeletal modelling.

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INTRODUCTION

Vertical jumping is an attractive model to use to study the coordination of movement as it is a relatively simple but fundamental movement, with a strong characteristic pattern of coordination (i.e. a proximal to distal pattern of segment extension). It has served as a model for some of the finest minds in biomechanics to study features of the musculoskeletal system that range from the stretch-shortening cycle [1] to biarticular muscle function [2–5]. One problem that has been of interest to a number of groups has been the muscular coordination strategy that is found during vertical jumping [4, 6, 7] and it has generally been argued that muscle activation follows a proximal to distal pattern [4, 6] that mirrors the pattern of segmental rotations. However, one thing that has not been addressed in this earlier work is how this pattern of activation is managed.

It is well known that for many movements we enjoy an abundance of possible motor control strategies [8]. This can be represented by considering the number of degrees of freedom (DOF) that are present for a given task. For instance, if we simplify vertical jumping and just consider the movement of one limb, we can count a potential 24 kinematic DOF (6 each for the foot, calf, thigh and pelvis segments). Alternatively, the same limb will be actuated by approximately 39 different muscles [9] each of which could be considered to be a DOF within the muscular control problem. These are thus complex systems, and the method by which they are managed for optimal performance is far from clear.

One way in which the coordination task can be simplified is if the number of DOF is reduced. This can be achieved by various means. Clearly, the structure of the musculoskeletal system itself can provide constraints – for instance, the bony and ligamentous structure of the joints can constrain the movement of adjoining segments reducing the number of DOF. Similarly, we have recently argued that other features of the lower limb provide mechanical constraints that reduce the DOF [10, 11]. Alternatively, the central nervous system can effectively simplify the control problem by coupling the activation of particular muscles, effectively reducing the DOF.

A key hurdle in understanding the coordination of human movement is thus in establishing how many effective DOF are present (sometimes called functional DOF). One tool that is useful for this purpose is principal component analysis (PCA) a data reduction technique that can be used to establish the effective DOF present within a data set. We have recently employed PCA to demonstrate that the sagittal plane moments impressed by the lower limb during vertical jumping exhibit only 2 functional DOF [12]. The purpose of this study was therefore two-fold: firstly, to expand on our previous work by examining the moment production in all 3 dimensions, and secondly, to use PCA to evaluate the functional DOF present within the muscular control problem.

MATERIAL AND METHOD

experimental approach to the problem

Firstly, the external mechanics of vertical jumping were measured using motion capture and force plate technologies, and the inter-segmental moments calculated using standard methodologies [13]. Secondly, a state of the art musculoskeletal model [14] was used to estimate the muscular forces that produced the observed movement. Thirdly, PCA was used to establish the functional DOF within the moment and muscle force data.

subjects

Twenty-one men (body mass = 85.0 ±8.9kg, height = 1.75 ±0.09m) and twelve women (body mass = 63.1 ±6.3kg, height = 1.67 ±0.07m) took part in this study. All subjects were healthy and free from musculoskeletal injury at the time of the study. The study was approved by the institutional review board of St Mary's University, Twickenham and all subjects provided written informed consent prior to participating in the study.

instrumentations

Force plate and motion capture technologies were employed in this study. The position of 18 retro-reflective markers placed on key anatomical landmarks of the lower limb [14] was quantified using a Vicon motion capture system (14 camera array, Vicon MX System, Vicon Motion Systems Ltd, Oxford, UK) sampling at 200Hz. The ground reaction force was collected at 1000 Hz using a Kistler force plate (Kistler 9287BA Plate, 600 × 900 mm, Kistler Instruments Ltd., Hampshire, UK) that was synchronised with the Vicon system, and then down-sampled to 200Hz.

procedure

Subjects first performed a standardised warm up consisting of body weight squats, lunges, inchworms, hip rotations and practice vertical jumps. They then performed 5 maximum effort vertical jumps with their hands on their hips. Recovery between jumps was self selected.

data analysis

The mechanical data captured in this study was analysed using FreeBody [14–18] a publicly available musculoskeletal model of the lower limb. FreeBody permits the estimation of the muscle and joint contact forces seen during movement and has been extensively tested in terms of its sensitivity to key modelling assumptions [18–21], its validity [14, 22, 23] and its reliability [24]. Firstly, all the data was filtered with 5th order Woltring filter (cut-off frequency = 10 Hz). Only the propulsive phase of the jump was taken for analysis – this was defined to be from the point that the marker on the right anterior iliac spine began to descend until the point where the ground reaction force was zero. Secondly the marker positions were used to specify the location and orientation of the rigid bodies used to model the pelvis and the thigh, calf and foot segments of the right lower limb using the method of Horn [25]. Next the kinematics of the individual segments were calculated based upon the position data and the anthropometry of de Leva [26]. The musculoskeletal model of the lower limb was based on the cadaveric data of Klein Horsman and colleagues [9] and was scaled based upon the size of the subject. The moment arms and lines of action of 163 muscle and 14 ligament elements were calculated based on the musculoskeletal geometry. The equations of motion of the lower limb were then posed based upon the geometry of muscle, joint and ligament forces and the external kinetics (GRF) and kinematics. There were 22 equations of motion and 193 unknowns – that is, an indeterminate problem. The optimal solution was found using the optimization toolbox of GNU Octave (https://www.gnu.org/software/octave/) by minimising the sum of the maximum muscle stress cubed and the ligament force relative to the failure limit of the ligaments cubed [17, 27, 28]. The maximum muscle force of each subject was scaled relative to their body mass, but if a solution could not be found for a particular frame then the maximum muscle force was incrementally increased. Only those trials for which a solution could be found for every frame were included in the final analysis.

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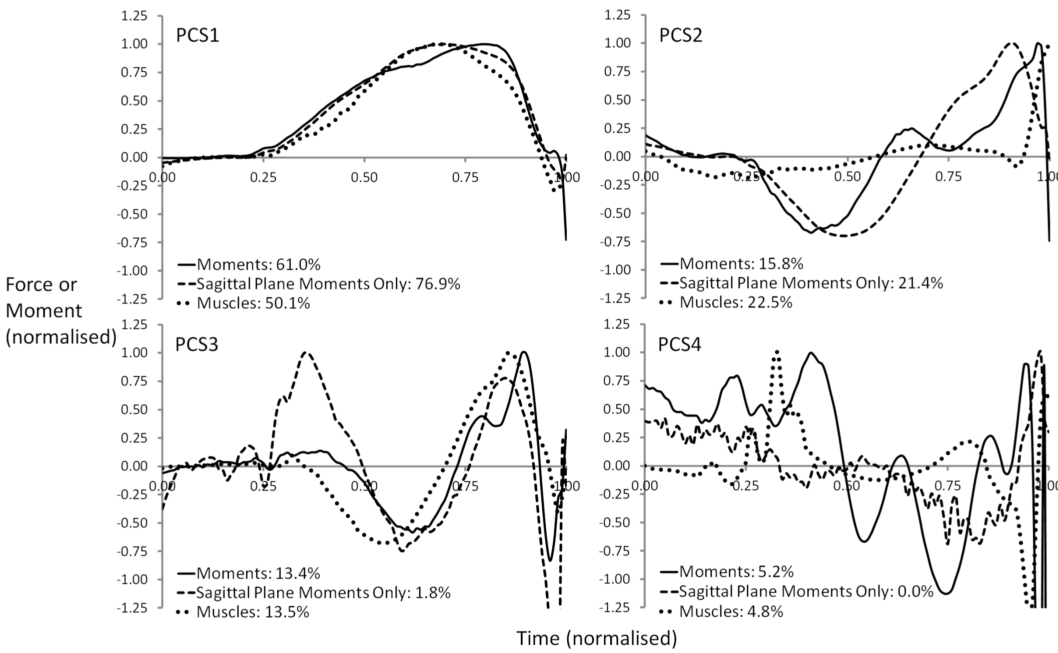
statistical analysis

The output from FreeBody was the time series representing muscle and joint contact forces during each jump. Each jump was time normalised such that the duration of the propulsive phase was 1 unit. Each data series was then spline interpolated in order to provide the values in increments of 1% of the propulsive phase. This then allowed composite curves of the time series of each subject to be created by calculating the average at each time point. Finally composite curves for the whole cohort were calculated by taking the average of each subject's composite curves.

Principal component analysis (PCA) was performed on the composite curves of the subject level muscle force and inter-segmental moment data. In particular, the 40 muscle force time series for each subject were combined in a 101 × 1320 input matrix for the first PCA and the 9 inter-segmental moment time series for each subject were combined in a 101 × 297 input matrix for the second PCA. The inter-segmental moments in the saggital plane only were analysed in a third PCA with a 101 × 99 input matrix. In each case, only the principal components (PCs) that were necessary to describe 90% of the variance in the data were retained. The original data was then projected onto the new (reduced) coordinate space and is presented here as the principal component scores (PCS).

RESULTS

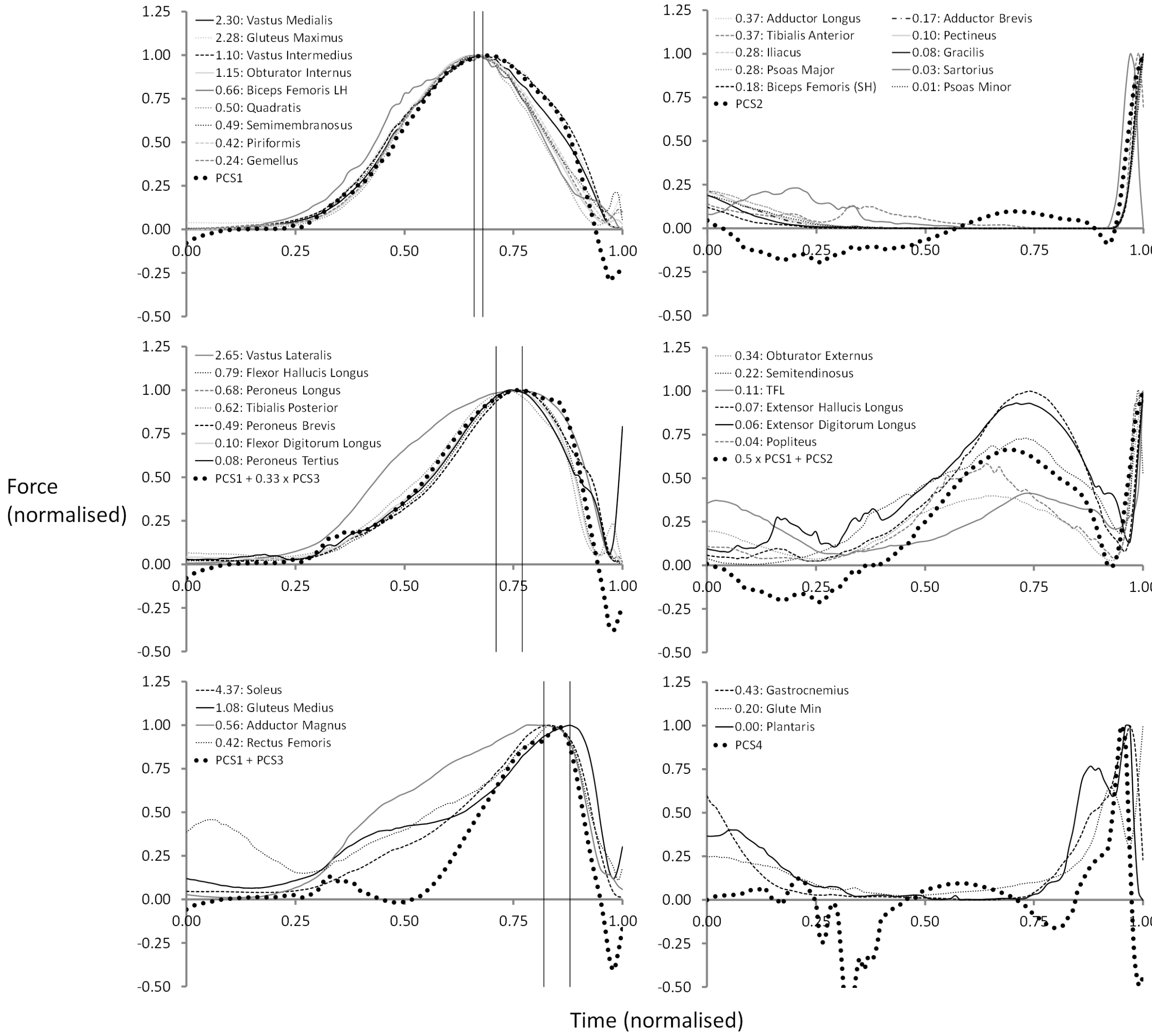
Only 2 PCs were required to explain over 90% of the variance in saggital plane only inter-segmental joint moments (PC1 = 76.9%, PC2 = 21.4%, sum = 98.3%), 3 PCs were required for the 3 dimensional inter-segmental joint moments (PC1 = 61.0%, PC2 = 15.8%, PC3 = 13.4%, sum = 90.2%), and 4 PCs were needed for the muscle forces (PC1 = 50.1%, PC2 = 22.5%, PC3 = 13.5%, PC4 = 4.8%, sum = 90.9%; Figure 1). There was a marked qualitative similarity between the PCS of the joint moments and the muscle forces for both the first and third PCs (Figure 1).



Percentage values given in the legend represent the proportion of the variance described by the given principal component

Figure 1. Principal component scores (PCS) for the principal component analysis of the inter-segmental moments and the muscle forces (normalised relative to the maximum moment or force)

There were a number of similarities between the force-time curves of the individual muscles. In particular, we identified 6 characteristic patterns that showed a clear correspondence with the PCS (Figure 2). For instance, the force-time graph for around half of the muscles resembled a simple bell curve (left hand side of Figure 2), however there was some variation in the timing of the peak force. For 9 of the muscles, including vastus medialis and intermedius, gluteus medius, and the long head of biceps femoris, the peak force occurred between 66% and 68% of the time interval. A further 7 muscles (including vastus lateralis) exhibited a peak force between 71% and 77%. Finally, the force in soleus, gluteus medius, rectus femoris, and adductor magnus peaked between 82% and 88% of the time interval. The shape of the force-time curve for the muscles that peaked between 66% and 68% was well approximated by the first PCS. In addition, the bell curve described by the first PCS could be shifted towards the right (delayed) by combining it with the third PCS (Figure 2).



The numbers given in the legend represent the peak value of each muscle force (N) relative to body weight (N). The vertical lines on the left hand side of the panel indicate the regions in which the peak muscle forces occurred. The bold dotted lines illustrate how the various time series can be represented by a linear combination of the principal component scores (PCS).

Figure 2. Mean muscle forces during vertical jumping (normalised relative to the maximum muscle force)

The peak joint contact forces ranged between 4.7 and 6.9 × body weight, and occurred prior to the peak in the ground reaction force (Figure 3). The tibiofemoral joint was relatively evenly loaded at the start of the jump, but became increasingly more medially loaded as the ground reaction force increased.

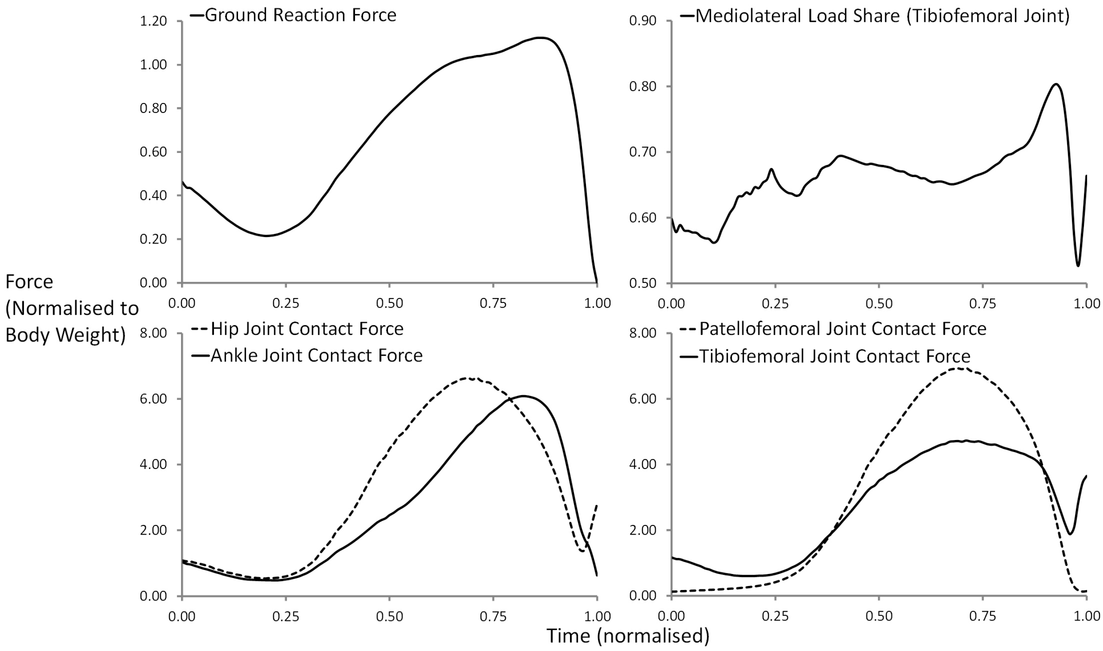


Figure 3. Mean ground reaction and joint contact forces during vertical jumping

DISCUSSION

In this study we found that the three-dimensional inter-segmental moments of 34 subjects performing a vertical jump can be represented by just 3 PCs. This is similar to our recent work where we showed that the sagittal plane inter-segmental moments during jumping could be described by 2 PCs [12]. It is notable here that only one further PC is required to capture 90% of the variance in the joint moments, despite the fact that the addition of the remaining two planes effectively triples the number of kinetic DOF in the input data. In our previous work, the input data comprised 189 individual jumps performed by 38 subjects, that is a 101 × 567 input matrix and there were 3 potential sources of variance within the data – inter- and intra-subject variability and inter-joint variability. We argued that two main conclusions were suggested by the reduction of the 567 potential DOF in the input data to just 2 functional DOF. Firstly, that the coordination strategy employed during vertical jumping is remarkably similar between and within individuals. Secondly, that the movement of the segments is mechanically coupled in some way (and we suggested, based on some of our earlier work [10], that this might be the mechanical coupling of the femur and tibia by the patella). The results of this study lend support to these arguments. In particular, only one further functional DOF is required to capture the variance in the frontal and transverse planes. This suggests that the movement in these planes is quite tightly linked to the movement in the sagittal plane. Furthermore, it seems unlikely that there is much inter-individual variability in the three-dimensional inter-segmental moments – if there were we would expect to need further PCs in order to capture this variability.

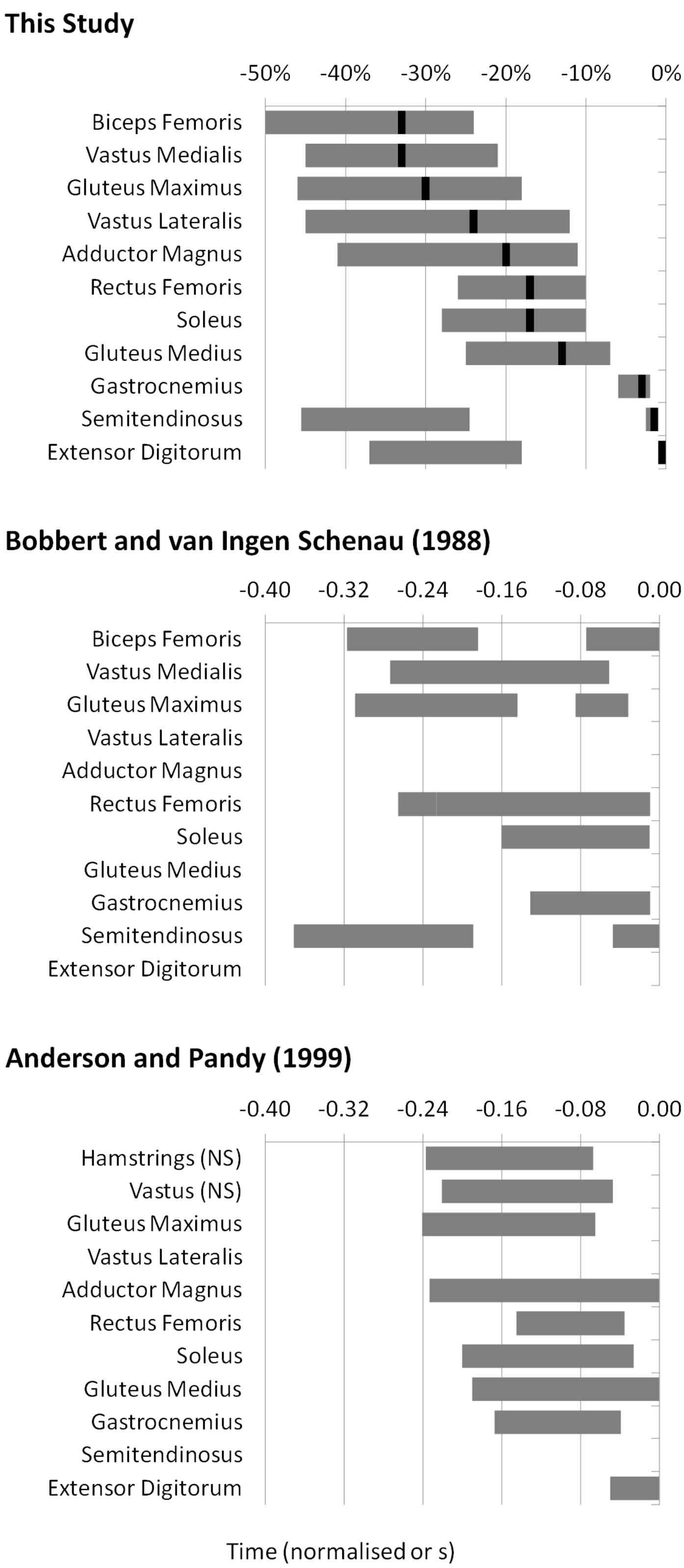


Figure 4. Comparison of muscle activations found in this study to Bobbert and van Ingen Schenau [6] and Anderson and Pandy [7]

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Grey bars indicate periods when muscular activation was above 75% of the maximum value reported during the jump. The data of Bobbert and van Ingen Schenau is based on the electromyographic record from one subject during a countermovement jump with hands on hips and only the period from the bottom of the countermovement is presented. The data of Anderson and Pandy is the muscle excitation history predicted by their model during a squat jump (starting from a static flexed position with arms across chest and no countermovement). In order to facilitate comparison, the muscular activations presented for this study only cover the time period from the bottom of the countermovement. The black lines for this study represent the time of peak muscle force and NS = not specified.

When comparing muscle activation patterns (Figure 4) to previous highly cited papers of Bobbert and van Ingen Schenau [6] and Anderson and Pandy [7] it is clear this study supports the contention that the control of muscular activation broadly follows a proximal to distal pattern [4,6]. In extending our understanding of the muscular control in vertical jumping, the PCA of the estimated muscle forces within this study demonstrated that 90% of the variance could be described by just 4 PCs. If we accept the suggestion that the production of inter-segmental moments is governed by 3 functional DOF, the additional PC that is required for the muscle forces seems most likely to describe the inter-individual variability in the way in which the muscle forces combine to impress the inter-segmental moments. This again represents a remarkable degree of inter-individual similarity in the muscular coordination strategy employed in maximal effort vertical jumping. It is well known that even if the movement outcome is the same, that there are many different muscular recruitment strategies that can be employed to achieve it – this is often described as the principle of motor redundancy or abundancy [8]. What these results suggest is that, despite the theoretical possibility of a wide range of muscular recruitment strategies, in practice, the strategies that are employed are much more constrained. The challenge for future researchers is to establish the mechanisms by which these constraints are applied.

The left hand side of Figure 2 demonstrates that the pattern of activation for over half of the muscles can be approximated by the simple parabola provided by the first PCS. However, these muscles can be categorised into 3 separate groups based upon the timing of the peak force. Figure 2 shows how the linear combination of the first and third PCS can shift the peak of the curve to provide this variation. It is notable that the third PCS has approximately double the frequency of the first PCS, and that the two PCS are in phase. This means that the two PCS can be readily combined to shift the peak of the muscular force curve in the way that is described. Researchers that use PCA to interrogate muscular activation strategies in the way that is used here need to become adept at seeing how the linear combination of PCS can produce different patterns of muscular force.

It is important to understand that the heavily reduced number of DOF in this study doesn't mean that the muscular activation patterns of all people are alike. The combination of PC1 and PC3 permit the expression of a wide number of different curves, with different amplitudes and where the peak force occurs at different times. Similarly, the relative timing of the peak forces for different muscle groups could vary between individuals, and this could still be described by the PCS found in this study. What these results do show is how tightly the muscular activations are constrained relative to each other.

CONCLUSIONS

In conclusion, this study builds on our previous work studying the DOF present in vertical jumping. Our results suggest that the 3 dimensional pattern of moment production is governed by just 3 DOF, implying that there is a great deal of inter-individual similarity in the way that individuals jump. Furthermore, the muscular forces that produce these moments are governed by 4 DOF, which provides evidence that the inter-individual variation in muscular coordination strategy is also quite tightly constrained.

REFERENCES

[1] Komi PV, Bosco C. Utilization of stored elastic energy in leg extensor muscles by men and women. Med Sci Sports. 1978;10:261-265.

[2] Bobbert MF, Huijing PA, van Ingen Schenau GJ. An estimation of power output and work done by the human triceps surae musle-tendon complex in jumping. J Biomech. 1986;19:899-906. https://doi.org/10.1016/0021-9290(86)90185-5

[3] Bobbert MF, Huijing PA, van Ingen Schenau GJ. A model of the human triceps surae muscle-tendon complex applied to jumping. J Biomech. 1986;19:887-898. https://doi.org/10.1016/0021-9290(86)90184-3

[4] Pandy MG, Zajac FE. Optimal muscular coordination strategies for jumping. J Biomech. 1991;24:1-10. https://doi.org/10.1016/0021-9290(91)90321-D

[5] Van Soest AJ, Schwab AL, Bobbert MF, et al. The Influence of the biarticularity of the gastrocnemius-muscle on vertical-jumping achievement. J Biomech. 1993;26:1-8. https://doi.org/10.1016/0021-9290(93)90608-H

[6] Bobbert MF, van Ingen Schenau GJ. Coordination in vertical jumping. J Biomech. 1988;21:249-262. https://doi.org/10.1016/0021-9290(88)90175-3

[7] Anderson FC, Pandy MG. A dynamic optimization solution for vertical jumping in three dimensions. Comput Methods Biomech. Biomech Eng. 1999;2:201-231. https://doi.org/10.1080/10255849908907988

[8] Latash ML. The bliss of motor abundance. Exp Brain Res. 2012;217:1-5. https://doi.org/10.1007/s00221-012-3000-4

[9] Klein Horsman MD, Koopman HFJM, van der Helm FCT, et al. Morphological muscle and joint parameters for musculoskeletal modelling of the lower extremity. Clin Biomech. 2007;22:239-247. https://doi.org/10.1016/j.clinbiomech.2006.10.003

[10] Cleather DJ. The patella: A mechanical determinant of coordination during vertical jumping. J Theor. Biol. 2018;446:205-211. https://doi.org/10.1016/j.jtbi.2018.03.013

[11] Cleather DJ, Southgate DFL, Bull AMJ. The role of the biarticular hamstrings and gastrocnemius muscles in closed chain lower limb extension. J Theor Biol. 2015;365:217-225. https://doi.org/10.1016/j.jtbi.2014.10.020

[12] Cushion EJ, Warmenhoven J, North J, et al. Principal component analysis reveals the proximal to distal pattern in vertical jumping is governed by two functional degrees of freedom. Front Bioeng. Biotechnol. 2019;7:193. https://doi.org/10.3389/fbioe.2019.00193

[13] Winter DA. Biomechanics and motor control of human movement (Third Edition). Hoboken, NJ: John Wiley & Sons; 2005.

[14] Cleather DJ, Bull AMJ. The development of a segment-based musculoskeletal model of the lower limb: introducing FreeBody. R. Soc. Open Sci. 2015;2:140449. https://doi.org/10.1098/rsos.140449

[15] Cleather DJ, Goodwin JE, Bull AMJ. An optimization approach to inverse dynamics provides insight as to the function of the biarticular muscles during vertical jumping. Ann.Biomed Eng. 2011;39:147-160. https://doi.org/10.1007/s10439-010-0161-9

[16] Cleather DJ, Goodwin JE, Bull AMJ. Erratum to: An optimization approach to inverse dynamics provides insight as to the function of the biarticular muscles during vertical jumping. Ann Biomed Eng. 2011;39:2476-2478. https://doi.org/10.1007/s10439-011-0340-3

[17] Cleather DJ, Bull AMJ. An optimization-based simultaneous approach to the determination of muscular, ligamentous, and joint contact forces provides insight into musculoligamentous interaction. Ann Biomed Eng. 2011;39:1925-1934. https://doi.org/10.1007/s10439-011-0303-8

[18] Cleather DJ, Bull AMJ. Lower-extremity musculoskeletal geometry affects the calculation of patellofemoral forces in vertical jumping and weightlifting. Proc Inst Mech Eng. [H]. 2010;224:1073-1083. https://doi.org/10.1243/09544119JEIM731

[19] Cleather DJ, Bull AMJ. Influence of inverse dynamics methods on the calculation of inter-segmental moments in vertical jumping and weightlifting. Biomed Eng. OnLine. 2010;9:74. https://doi.org/10.1186/1475-925X-9-74

[20] Cleather DJ, Bull AMJ. Knee and hip joint forces: Sensitivity to the degrees of freedom classification at the knee. Proc Inst Mech Eng. [H]. 2011;225:621-626. https://doi.org/10.1177/0954411911399975

[21] Southgate DF, Cleather DJ, Weinert-Aplin RA, et al. The sensitivity of a lower limb model to axial rotation offsets and muscle bounds at the knee. Proc Inst Mech Eng. [H]. 2012;226:660-669. https://doi.org/10.1177/0954411912439284

[22] Ding Z, Nolte D, Kit Tsang C, et al. In vivo knee contact force prediction using patient-specific musculoskeletal geometry in a segment-based computational model. J Biomech Eng. 2016;138:021018-021018. https://doi.org/10.1016/0021-9290(81)90035-X

[23] Price PDB, Gissane C, Cleather DJ. The evaluation of the FreeBody lower limb model during activities of daily living. Bioengineering16 [Internet]. 2016 [cited 2017 Feb 8]. Available from: https://www.researchgate.net/publication/307546172_The_evaluation_of_the_FreeBody_lower_limb_model_during_activities_of_daily_living.

[24] Price PDB, Gissane C, Cleather DJ. Reliability and minimal detectable change values for predictions of knee forces during gait and stair ascent derived from the FreeBody musculoskeletal model of the lower limb. Front Bioeng Biotechnol. 2017;5:74. https://doi.org/10.3389/fbioe.2017.00074

[25] Horn BKP. Closed form solution of absolute orientation using unit quaternions. J Opt Soc Am A. 1987;4:629-642. https://doi.org/10.1364/JOSAA.4.000629

[26] de Leva P. Adjustments to Zatsiorsky - Seluyanov's segment inertia parameters. J Biomech. 1996;29:1223-1230. https://doi.org/10.1016/0021-9290(95)00178-6

[27] Crowninshield RD, Brand RA. A physiologically based criterion of muscle force prediction in locomotion. J Biomech. 1981;14:793-801. https://doi.org/10.1016/0021-9290(81)90035-X

[28] Raikova RT. Investigation of the influence of the elbow joint reaction on the predicted muscle forces using different optimization functions. J Musculoskelet. Res. 2009;12:31-43. https://doi.org/10.1142/S021895770900216X

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