Proximal and distal constraints reduce dimensionality of vertical jumping tasks

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The purpose of this study was to examine motor control strategies employed to control the degrees of freedom when performing a lower limb task with constraints applied at the hip, knee and ankle. Thirty-five individuals performed vertical jumping tasks: hip flexed, no knee bend and plantar flexed. Joint moment data from hip, knee and ankle was analysed using principal component analysis (PCA). In all, PCA performed, a minimum of two and maximum of six principal components (PCs) were required to describe the movement. A proximal to distal reduction in variability was only observed for the hip flexed and no knee bend conditions. Collectively, the results suggest a reduction in the dimensionality of the movement occurs, despite the constraints imposed within each condition and would suggest dimensionality reduction and motor control strategies are a function of the task demands.

KEYWORDS: degrees of freedom, motor control, dimensionality.

INTRODUCTION: A question which has long concerned scientists and researchers with an interest in human movement is how individuals are able to control the many degrees of freedom (DOF) whilst performing smooth, flowing, and seemingly effortless actions. When performing motor tasks, there will be more than one coordination pattern available to the individual, which is said to represent redundancy of the motor system (Newell & Vaillancourt, 2001). This motor redundancy, however, provides functional benefit to the performer as it allows flexibility and adaptability to the ever-changing performance constraints. To effectively undertake goal directed movement, it is proposed that the system produces synergies (covariance between joints) to reduce the complexity of controlling many DOFs (Latash et al., 2007). Researchers have sought to investigate the notion by using statistical approaches such as principal component analysis (PCA), which reduces the dimensionality of data. Using this approach, Shemmell et al. (2007) found just two principal components (PCs) were required to describe the relationship between three joint angles during the swing phase of a walking task, suggesting a coupling or *synergy* between these joints.

Many movement tasks require the control of proximal and distal segments for efficient movement outcomes. However, noise disturbances applied to proximal joints or distal joints can differentially affect the overall movement dynamics and control of the task (Salmond, et al., 2017; Nguyen & Dingwell, 2012). One approach to gain insights into the motor control strategies employed to control the DOF present within a task is to apply constraints to parts of the system. However, in much of the published literature there has been a bias towards analysing proximal and distal upper limb motor control strategies. The nature of upper limb tasks, however, usually requires the distal aspect of the limb (e.g. hand) to be free, compared to many lower limb tasks where the distal aspect (e.g. foot) is usually in contact with a surface, either throughout (e.g. sit to stand) or in portions of the movement task (e.g. jumping). Consequently, this may affect the proximal and distal motor control strategies and control of DOF throughout the movement and warrants further investigation.

Therefore, the purpose of this study was to examine the motor control strategies employed to control the degrees of freedom of a lower limb task with constraints applied at the hip, knee and ankle. A vertical jump was chosen as a suitable task due to the requirement of a proximal to distal extension of the lower limb. The study focused on determining the changes in contribution of DOF between conditions, along with understanding the control of proximal to distal joints within the sagittal plane. To determine motor control strategies and the control of DOF, a multivariate statistical tool, principal component analysis (PCA) was used.

METHODS: Thirty-five healthy individuals (males = 22, females = 13) volunteered to take part in this study (mean ± SD; age = 26.0 ± 5.5 years, height = 174.8 ± 8.9 cm, body mass 78.5 ± 14.1 kg). Participants were free from musculoskeletal injuries and provided written informed consent before testing began. The experimental procedure was approved by the ethics sub-committee at the institution where the research took place.
Eighteen reflective markers were placed on the pelvis and on the right lower limb in accordance with the use of FreeBody software (Cleather et al., 2013). During testing, participants completed a standardised warm up prior to completing vertical jump tasks. The three vertical jump tasks were: starting from a hip flexed position (HF), jumping without bending the knee (NKB), and jumping starting in a plantar flexed position (PF). The data collection was part of a larger collection of data where multiple types of jumps were performed across different testing sessions in a randomised order. As a result of this, not all participants completed each jump condition. Twenty-one participants completed the hip flexed and no knee bend conditions, and twenty-two participants completed the plantar flexed condition. Participants completed five maximal effort trials with a self-selected recovery period between trials to reduce effects of fatigue.
Kinematic data were collected using a Vicon motion capture system (Vicon MX System, Nexus 2.2 software, Vicon Motion Systems Ltd, Oxford, UK) with fourteen LED cameras tracking the reflective markers at a sampling frequency of 200Hz. Kinetic data were collected via two force plates positioned flush to the laboratory floor (Kistler Type 9287BA, Bioware 3.24 software, Kistler Instruments Ltd, Hampshire, UK), at a rate of 1000Hz and synchronised with the Vicon system. Net joint moments (NJM) in the sagittal plane were calculated for hip, knee and ankle using a standard inverse dynamics calculation (Winter, 2005) within the FreeBody software (Cleather & Bull, 2015).
Within this study, hip, knee and ankle net joint moments were used within several PCA, to analyse differences between jumping conditions. PCAa included data from all participants, trials and joints from all jump conditions (rows 101 x columns 947), PCAc included data from all participants, trials and joint from each jump condition separately (HF: 101 x 300, 101 x 314, PF: 101 x 333), PCAj included data from all participants and trials from all jump conditions conducted separately for each joint (Hip: 101 x 317, Knee: 101 x 317, Ankle: 101 x 317) and finally PCAcj included data from all participants and trials from each jump condition conducted separately for each joint (HF: Hip, Knee, Ankle: (101 x 100), NKB: Hip, Knee, Ankle: (101 x 106), PF: Hip, Knee, Ankle: (101 x 111). PCA were performed in Matlab (The MathWorks, Inc., M A, version 2017a) using the *pca* function.

RESULTS: Analysis from PCAa showed four PCs were required to retain over 90% of the information within the dataset. When combining all data for each jump condition separately (PCAc), three PCs were required to explain over 90% of the variance within the data set for the hip-flexed and no knee bend conditions, whereas five PCs were required for the plantar-flexed condition.

Figure 1 presents PC1, 2 and 3 waveforms for each jump condition and demonstrates how each joint was loaded onto each jump condition from PC1, 2 and 3. Data within this figure is from PCAc.

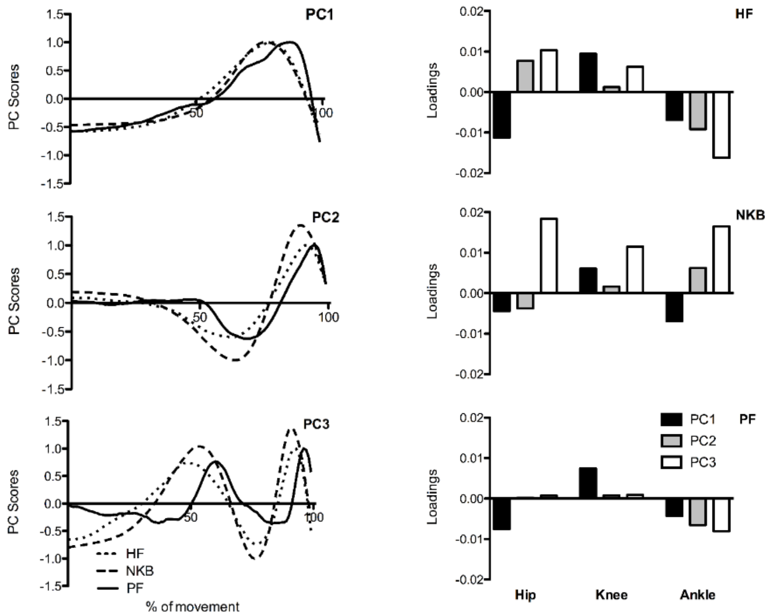

Figure 1. PC1, 2 and 3 score waveforms for each jump condition (left panel) and loadings on PC1, 2 and 3 for each jump condition (right panel). HF = hip flexed, NKB = no knee bend, PF = plantar-flexed.

Table 3 shows results from PCAj and PCAcj. For each PCA from PCAj only three PCs were retained. A maximum of six PCs were required in PCAcj analysis.

Table 3. Percentage of explained variance from PCAj.

	PC1	PC2	PC3	PC4	PC5	PC6	Total
All Conditions (PCAj)							
Hip	69.7	19.5	4.6				93.8
Knee	67.5	18.0	7.7				93.2
Ankle	74.1	15.7	4.1				93.9
All Conditions (PCAcj)							
HF							
Hip	69.7	15.3	5.1				90.1
Knee	74.8	12.8	7.1				94.7
Ankle	83.7	8.9					92.6
NKB							
Hip	47.9	26.5	11.9	4.9			91.2
Knee	70.5	22.3					92.8
Ankle	77.7	16.4					94.1
PF							
Hip	59.9	13	6.6	4.8	3.9	2.9	91.1
Knee	70.4	15.7	5.5				91.6
Ankle	64.8	17.6	6.3	3.1			91.8

HF = Hip flexed, NKB = no knee bend, PF = plantar flexed

DISCUSSION: The aim of the current study was to understand motor control strategies employed in vertical jumps under different task constraints and to determine the control of the functional DOF within each task. The main hypothesis was that a reduction in the dimension of the DOF would occur for each condition. The results were consistent with this hypothesis, as evidenced by the requirement of only three to six PCs being retained to capture the characteristics of the three conditions for each PCA performed. Interestingly though, whilst the temporal pattern of moment production within each jump condition were similar the reduction in dimensionality of each task were not, with the plantar flexed condition showing the most variation compared to the hip flexed and no knee bend conditions. We also showed slight differences in variation at the proximal and distal joints, with a proximal to distal decrease in variation occurring for hip flexed and no knee bend conditions. The plantar flexed condition again showed differences within this result with the least variation occurring at the knee joint.

The results of this study show that the dimensionality of jumping with added constraints can be reduced to just a few functional DOF. Within each PCA performed a maximum of six PCs and a minimum of two PCs were retained. This reduction in dimensionality of complex coordinated movements has been reported previously in other tasks (Bockemühl, Troje & Durr, 2009). Despite some differences in the dimensionality reduction in each task there is similarity in the pattern of waveforms which can be observed in Figure 1. Comparisons of the temporal shape of PC waveforms are made across each jump condition and between each joint. Whilst the shape of the waveforms are similar, the information captured within each PC varies. For instance, PC1 for plantar flexed condition is almost entirely described by the hip and knee moments, this would indicate a coupling between the hip and knee, such that they move in phase with each other. This was not observed as clearly within the other two conditions. Collectively this information would support the concept of motor equivalence, where the same movement outcome can be achieved under varying conditions (jump conditions in this study) and limb control strategies (joint moment production in this study); a notion supported within the literature (Mattos, Kuhl, Scholz, & Latash, 2013).

CONCLUSION: This study highlights the system's ability to adapt to constraints in a multi-joint task. Despite constraints being applied at each lower limb joint, there were remarkable similarities as well as differences in the motor control strategies, in order to realise the task goal. The dimensionality of each movement was similarly reduced for hip flexed and no knee bend conditions, with a lesser reduction occurring for the plantar flexed condition. Equally, the temporal pattern of movement production share resemblances for each condition. In contrast, we observed differences in loadings between conditions, suggesting the utilisation of each joint differed in each condition to ensure the task was performed. Interestingly it was the constraint applied at the ankle which showed the greatest difference in strategy, with larger variation within the movement and a lack of a clear proximal to distal reduction in variability. With the added balance requirement of this task, it is likely the demand of the task plays a big part in how the system controls the DOF. This research supports the notion the CNS utilised the redundancy within the system in order to carry out specific tasks under differing constraints.

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