Human Movement Science 64 (2019) 67–74

Contents lists available at ScienceDirect

Human Movement Science

journal homepage: www.elsevier.com/locate/humov

Evaluating movement performance: What you see isn't necessarily what you get

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A B S T R A C T

With the goal of reducing injury and enhancing performance, movement screening tools score an individual's movements against a standard and because it is a predictor of injury symmetry is often included in the score. Movement quality screening tools only consider kinematic asymmetry, which may underestimate the degree of asymmetry present during movement. Consider joint forces: if these forces are atypical, additional stress is created and control is reduced, which can lead to injury if the asymmetry is not addressed. The purpose of this study is to investigate movement symmetry in the kinematic, kinetic and muscle activity components of movement during a parallel squat.

Thirty-four healthy individuals completed five body-weight, parallel squats. A motion capture system, two portable force plates, and electromyography (EMG) sensors recorded the squat motion, ground reaction forces and muscle activity. The variables of interest were the joint angles, joint moments, and EMG waveforms. Cross-correlations and normalized root-mean-square values were calculated for the left and right ankles, knees, and hips for each variable. A repeated-measures analysis of variance (ANOVA) tested for differences in symmetry (cross-correlation and nRMS) between the kinematic, kinetic, and muscle activity components at the ankle, knee, and hip during the squat.

At all joints the kinematic component had the highest degree of symmetry, and the kinetic and muscle activity components showed poorer symmetry, with the muscle activity component being the least symmetric. The differences in symmetry between movement components suggests that movement performance evaluations should not rely exclusively on kinematics and observation to identify potential movement faults.

1. Introduction

The goal of current movement screening tests is to identify movements that might increase injury risk and hamper physical performance (Frost, Andersen, et al., 2013; Gamble, 2014; McGill, Anderson, & Horne, 2012; van Dijk, Smorenburg, Visser, Nijhuis–van der Sanden, & Heerkens, 2017; Whittaker et al., 2017). Typically, movement screening tests compare an individual's movement pattern to the desired movement pattern on a series of fundamental movements with better scores given for matching the desired movement patterns and lower scores for deviations from the desired patterns. Some examples of movement quality screening tests are the Functional Movement Screen (FMS) (Cook, Burton, & Hoogenboom, 2006a,b), the Netball Movement Screening Tool (Reid, Vanweerd, Larmer, & Kingstone, 2015), and the Athletic Abilities Assessment (McKeown, Taylor-McKeown, Woods, & Ball, 2014). The tests listed above and other tests that evaluate movement performance consider variables such as speed (McGill et al., 2012; Woods, McKeown, Haff, & Robertson, 2016), strength (Frost, Andersen, et al., 2013; McGill et al., 2012; Woods et al., 2016), endurance (McGill et al., 2012; Woods et al., 2016), joint range of motion (Frost, Andersen, et al., 2013; McGill et al., 2012), stability (Giblin, Collins, & Button, 2014; Woods et al., 2016), and coordination (Fleishman, 1972; Giblin et al., 2014). Because it is a strong predictor of injury risk, an additional variable of interest is asymmetry (Baumhauer, Alosa, Renstrom, Trevino, & Beynnon, 1995; Frost, Andersen, et al., 2013; Hellsing, 1988; Knapik, Bauman, Jones, Harris, & Vaughan, 1991; Zifchock, Davis, Higginson, McCaw, & Royer, 2008).

By definition, asymmetry is an imbalance, whether it be between the right and left sides of the body, a joint's agonists and

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https://doi.org/10.1016/j.humov.2019.01.003
Received 9 August 2018; Received in revised form 13 December 2018; Accepted 7 January 2019
Available online 16 January 2019

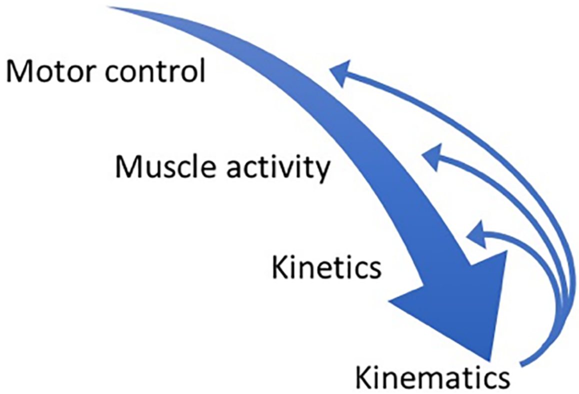

Fig. 1. Biomechanical model for assessing movement symmetry at various components of movement.

antagonists or the opposing sides of a joint (Cook et al., 2006a,b; Hellsing, 1988; Knapik et al., 1991). In movement screening tests an asymmetry is a visible deviation from the desired movement pattern. Of course, we expect that the kinematic deviations are due to disruptions in the kinetics or muscle activity. For example, the shoulder complex depends on the surrounding muscles to provide stability, range of motion, and strength (Page, 2011). A strength deficit in the agonist muscle changes the kinematics as well as the patterns of joint forces, ultimately increasing the risk of injury through structural damage (Page, 2011). In another example, research found that diminished hamstring muscle endurance and quadriceps strength were predisposing factors for knee injuries (Devan, Pescatello, Faghri, & Anderson, 2004) and concluded that correcting muscle imbalances may be the key to preventing overuse knee injuries (Devan et al., 2004). Given these examples, it is important to assess and address asymmetries to decrease the risk for injury.

Movement quality screening tests that evaluate asymmetry focus on the kinematics. For example, five of the seven movements in the FMS score the right and left sides separately and if the scores differ between the right and left sides, asymmetry is noted and the lower of the two scores is used to compute the composite score. This evaluation of asymmetry is kinematic as the FMS system only uses visual cues and observations of performance to evaluate the movement. Using only kinematic observation may underestimate the degree of asymmetry present in a movement. Clearly, an asymmetric movement pattern suggests asymmetric joint loads but to date, there is no research examining if symmetric motions are always the result of symmetric loads. Frost and colleagues found that firefighters can change their FMS score after receiving feedback on their performance (Frost, Beach, Callaghan, & McGill, 2013). If individuals can change their movement patterns, then they must have done so using altered kinetics. How this alteration is achieved is unknown. This disconnect between the kinetics and visual outcomes of movement was also noted by Winter when he mentioned that it is not realistic to infer what forces are acting to cause motion based solely on the kinematics (Winter, 1984). He stated that while multiple forces cause motion, the kinematics describe only the final outcome of all the forces (Winter, 1984). Movement production is a repeating series of events, starting with motor control, which stimulates muscle activity, in turn producing forces around the joints, which results in the kinematic outcomes of the movement (Fig. 1), which provides feedback to make adjustments before the next movement is produced. The assumption that kinematic symmetry (or asymmetry) reflects what is happening at the kinetic and muscle activity components may misrepresent the degree of true symmetry and therefore the risk of injury.

The purpose of this study is to explore symmetry of the kinematic, kinetic, and muscle activity components of movement during a parallel squat. Based on the assumption currently made by movement quality screening tests, we hypothesize that all components of movement (kinematic, kinetic, and muscle activity) will show the same degree of movement symmetry.

2. Methods

2.1. Participants

Thirty-four healthy young adults (17 males and 17 females, age: 22.2 years ± 2.9 years, mass: 71.6 kg ± 13.7 kg, height: 1.74 m ± 0.08 m) participated in the study. Written consent was obtained prior to participation and the protocol was approved by Queen's University General Research Ethics Board.

2.2. Instrumentation

A motion tracking system with 13 Oqus cameras (Qualysis Track Manager, Qualysis, Gothenburg, Sweden; sampling frequency = 100 Hz) recorded the squat motion. Twenty-three optical tracking markers (14-mm diameter) were placed on specific anatomical landmarks to define the proximal and distal ends of the pelvis, thighs, shanks, and feet on the right and left lower limbs. Two portable force plates (Bertec Inc., Columbus, OH, USA; sampling frequency = 100 Hz) measured the ground reaction force under the left and right feet. Wireless surface electromyographic (EMG) sensors (Delsys, Boston, MA, USA; bandwidth = 20–450 Hz, sampling frequency = 1925.93 Hz) were placed on shaved, abraded and cleaned skin surfaces to sample the muscle activity of six muscles on each leg (gluteus maximus, biceps femoris, rectus femoris, vastus medialis, vastus lateralis, gastrocnemius).

2.3. Data collection

Participants performed five parallel squats trials. Five squats minimized the effect of fatigue and pilot work showed that additional trials did not significantly reduce variability. For each trial, the participant squatted down until they touched a platform and then came back up to their starting position. The platform was adjusted to a height where the participant's thighs were parallel to the ground at the bottom of their squat. The speed of the squat was self-selected. The participant received no additional instructions between trials. There was 30 s of rest between trials.

2.4. Data analysis

The motion, force plate, and EMG data were synchronized by Qualysis Track Manager (version 2.14, Qualysis, Gothenburg, Sweden). The three-dimensional angles and moments for the left and right ankles, knees and hips were computed using Visual 3D (version 5, C-Motion Inc., Germantown, MD, USA). Because the motion of the squat occurs primarily in the sagittal plane, only sagittal plane data was analyzed, similar to other studies examining squat movements (Comfort, Jones, Smith, & Herrington, 2015; Dahlkvist, Mayo, & Seedhom, 1982; Salem, Salinas, & Harding, 2003). The joint angle data were not filtered as the quasi-static nature of the squat movement coupled with the fidelity of the motion capture system generated little to no signal noise. Using a custom Matlab program (R2017b, MathWorks Inc., Natick, MA, USA), the moments were filtered with a dual-pass Butterworth filter with a cutoff of 10 Hz. The EMG data were up-sampled from 1925.93 Hz to 2000 Hz, the DC offset was removed, full-wave rectified and filtered (dual low-pass at 2 Hz). The EMG data were normalized by the peak EMG activity of all squat trials for each of three representative muscles. The gastrocnemius represented the ankle muscle activity as it is the main ankle extensor during a squat (McCaw & Melrose, 1999; O'Shea, 1985). The vastus lateralis represented the knee muscle activity as it has the greatest activity during a squat movement (Dionisio, Almeida, Duarte, & Hirata, 2008). The gluteus maximus represented the hip muscle as it is one of the main extensors during the squat movement (McCaw & Melrose, 1999; O'Shea, 1985).

The threshold for initiation (start of the down phase) and termination (end of the up phase) of each squat was determined by averaging the velocity of the left and right greater trochanter markers and taking 1% of the maximum velocity. All data were normalized to 100 percent of the squat cycle. At each of the ankle, knee and hip joints the cross-correlation between the left and right joint angles, moments and selected EMG profiles were computed. To compute a normalized RMS value the typical RMS value is computed and then divided by the mean of the left and right variables (Eq. (1)) (A Dictionary of Physics, 2009). The correlations represent the similarity between the left and right sides while the RMS represents the magnitude difference between the left and right sides.

$$\mathrm{nRMS} = \frac{\sqrt{\frac{1}{100}\sum_{i=1}^{100}(\mathrm{L}_i - \mathrm{R}_i)^2}}{(\bar{L} + \bar{R})/2} \tag{1}$$

Normalized Root Mean Squat; 100 is the number of normalized samples; i is the sample number, L is the left leg variable, R is the right leg variable.

2.5. Statistical analysis

A repeated-measures analysis of variance (ANOVA) tested whether there was a difference in symmetry measures (cross-correlation and nRMS) between the kinematic, kinetic, and muscle activity at the ankle, knee, and hip. Comparison were not made between joints. Significant effects were followed up with Bonferroni-adjusted post-hoc comparisons. Statistical significance was set at $p < 0.05$.

3. Results

The average knee angle range was 89.2°, and the moment about the knee reached an average maximum of 1.01 Nm/kg. At each joint, there were differences in the cross-correlations and normalized RMS values between the kinematic, kinetic, and muscle activity components (Table 1). Notice that the kinematic variable, represented by joint angles, shows the highest correlation with the smallest standard deviation while the muscle variable, represented by the EMG activity, shows the lowest correlation with the largest standard

Table 1
Ensemble average correlations and normalized RMS between right and left sides for the kinematic (angle), kinetic (moment), and muscle activity data. *All comparisons between the components of movement are statistically significant ($p < 0.05$).

Measure	Component	Ankle*	Knee*	Hip*
Correlation	Kinematic	0.995 (0.003)	0.999 (0.001)	0.999 (0.000)
	Kinetic	0.77 (0.13)	0.96 (0.02)	0.95 (0.026)
	Muscle	0.45 (0.23)	0.82 (0.08)	0.74 (0.13)
nRMS	Kinematic	0.038 (0.02)	−0.040 (0.02)	0.028 (0.017)
	Kinetic	−0.55 (0.25)	0.27 (0.14)	−0.28 (0.13)
	Muscle	0.70 (0.38)	0.40 (0.21)	0.49 (0.99)

deviation. A sample of data for one participant is shown in Fig. 2. In the figure, all three joints show similar joint angle patterns for the left and right sides, with more variability in the moments and EMG waveforms.

In Fig. 3, the left and right variables are plotted against each other for each of the three components of movement at the ankle, knee and hip. In the angle plots the data are clustered about the line of symmetry. However, in the kinetic component and the muscle component, the data about the line of symmetry are more dispersed indicating an increased deviation from symmetry between the left and right joints. This is also noticeable in the ellipses that were fit to the data. For each ellipse, a size ratio was calculated by dividing the short axis by the long axis. For the knee and hip angle plots no ellipse was found as a location of the short axis could not be defined due to the homogeneity of the data's dispersion about the long axis. For the ankle angle, the ellipse ratio is 0.1432. As for the moments, the ellipse ratios are 0.4120, 0.3054, and 0.3322 for the ankle, knee and hip, respectively. Lastly, for the muscle activity component, the ellipse ratios are 0.6013 for the vastus lateralis and 0.5898 for the gluteus maximus. The gastrocnemius did not generate an ellipse as there are an infinite number of major axes possible due to the dispersion of the data.

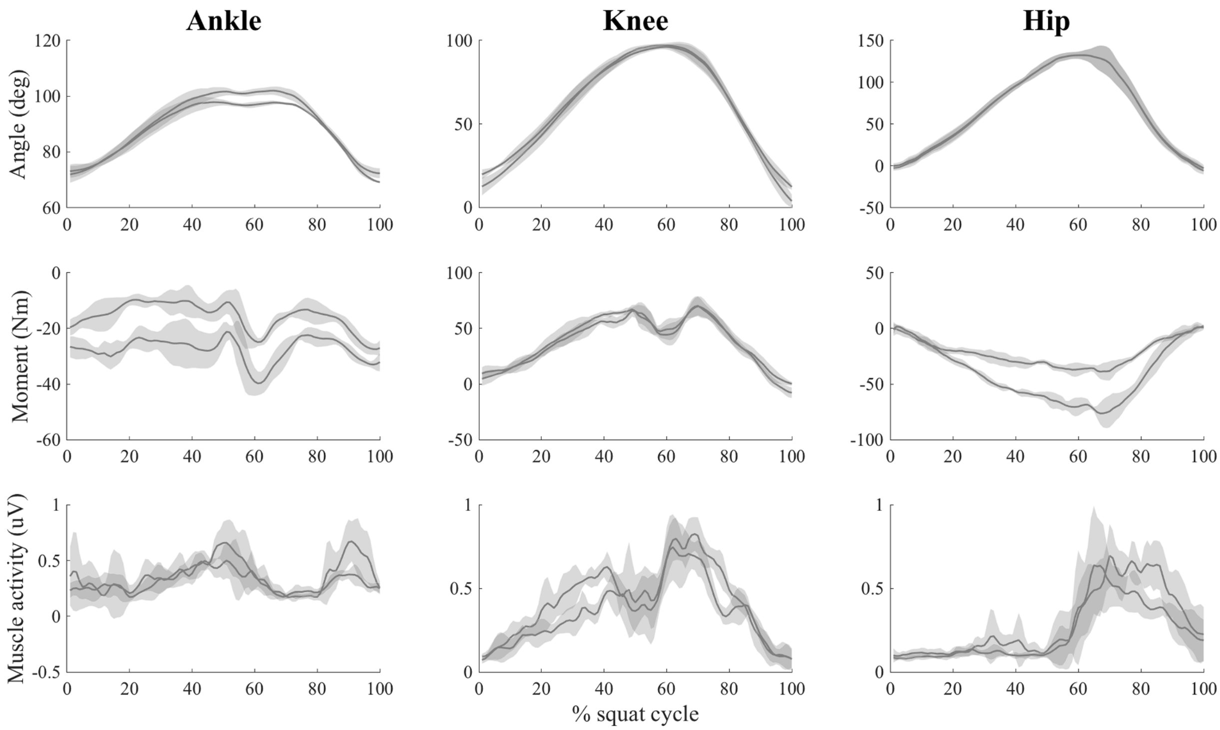

Fig. 2. Sample of data for one participant. The top row represents the kinematic data (joint angles) of the ankle, knee, and hip. The second row represents the kinetic data (joint moments) of the ankle, knee, and hip. The bottom row represents the muscle activity data of the gastrocnemius, vastus lateralis, and gluteus maximus. The black lines represent the average data of all 5 trials for the left and right sides and the lighter grey filling represents one standard deviation.

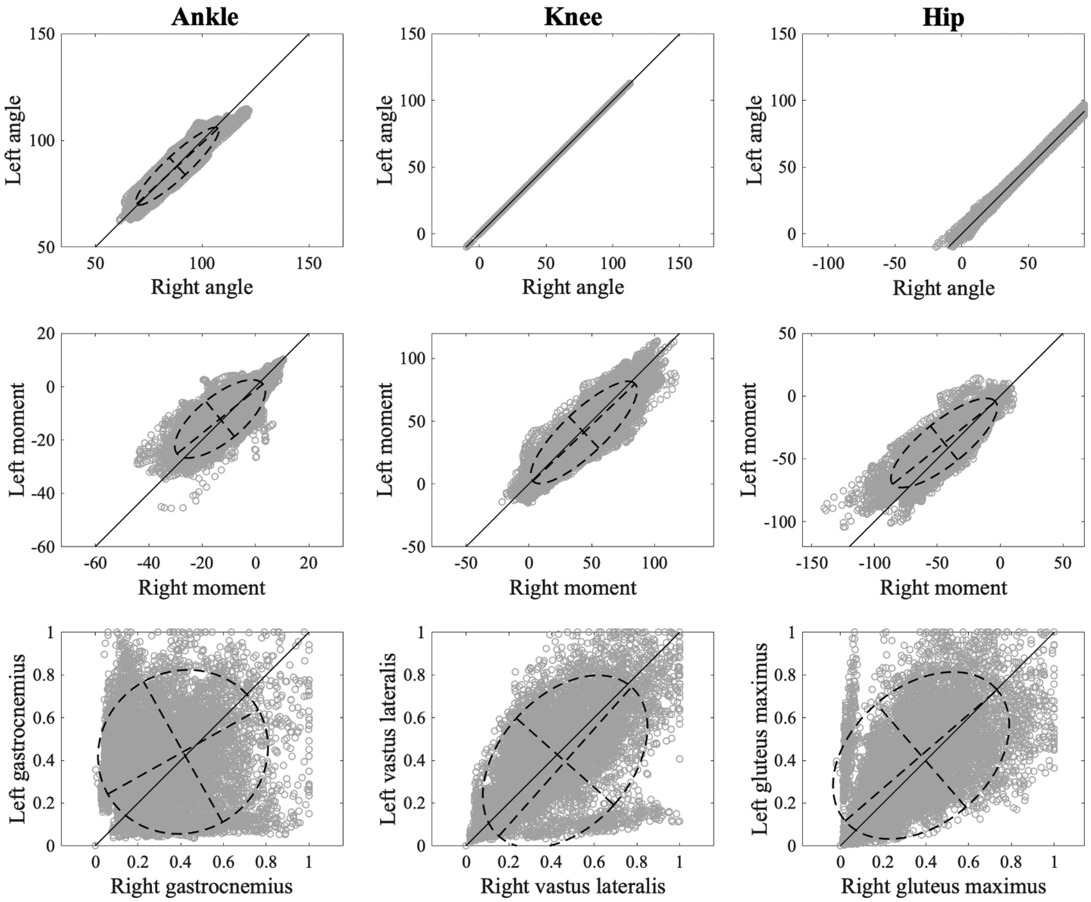

Fig. 3. Comparison of left and right variables at each time point in the squat cycle for all participants. The black line represents perfectly symmetric movement execution between the left and right variables. The ellipse represents the best fit for the data points. Subplot A represents the kinematic component, subplot B represents the kinetic component, and subplot C represents the muscle component.

4. Discussion

4.1. Primary findings

The purpose of this study was to examine the degree of symmetry in the kinematic, kinetic, and muscle activity components of movement during a parallel squat. In doing so, we address the assumption that kinematic observations of movement reflect the underlying kinetic and muscle activity patterns. The findings show significant differences in symmetry at the three components of movement and that the degree of symmetry decreases as one moves from the kinematic to the kinetic and then to the muscle activity component. The average squat depth in this study, as determined by the knee angle range, was 89.2°, which is in line with other studies that have examined the parallel squat (Escamilla et al., 1998, 2001; Hattin, Pierrynowski, & Ball, 1989). Additionally, the average peak moment of force for the knee was 1.01 Nm/kg, which coincides with other research (Salem et al., 2003).

4.2. Limitations

The major limitation of this study is the potential error associated with the measurement of each component of movement. While the motion tracking system calibration showed a standard tracking error of less than 0.04 mm, there is error in placing the markers on the anatomical landmarks that would affect the joint angular measures. Since the squat is a symmetric and highly constrained motion, symmetric kinematics are expected. The results from the study indicate that symmetric kinematics were obtained, which assures proper placement of the markers on the appropriate anatomical landmarks. The kinetic measures were obtained via inverse dynamics, incorporating motion tracking with center of pressure and force data. Certainly, errors in marker placement would create biased kinetic calculations. However, research from Holden and colleagues evaluated the difference between skin surface marker placement and a bone attachment technique to quantify surface movement errors (Holden et al., 1997). They found acceptable magnitudes of error and concluded that the errors would likely not affect clinical interpretation of data containing surface movement errors. Moreover, on the issue of anthropometry, research by Pearsall and Costigan addressed the errors in body segment parameters and how they influence biomechanical analysis of human movement (Pearsall & Costigan, 1999). Using an inverse dynamic analysis, they performed iterative kinetic calculations using various segment parameter values. They found that segment parameter variations significantly affected most of the kinetic estimates produced; however, the magnitude of these effects was less than 1% of body weight (Pearsall & Costigan, 1999). Because the current study compares each participant's right and left lower limbs any systematic errors in anthropometric assumptions are reduced considerably. For the muscle activity component, although the electromyography sensors used in this study offer great accuracy (168 nV/bit) (Delsys Incorporated, 2013), they have limitations. The sensors were positioned on the body according to SENIAM guidelines (Hermens et al., n.d.) and a measuring tape was used to increase accuracy. However, there could still be measurement errors associated with their placement. The skin surfaces were also shaved and scrubbed with rubbing alcohol prior to sensor placement. A simple alcohol cleaning, as performed in this study, is sufficient skin preparation as there is minimal risk of movement artifacts (Konrad, 2005) in quasi-static, controlled movements such as the squat performed in this study. Lastly, the EMG data were task-normalized to the peak of the normal squat condition to remove amplitude differences across the legs. This normalization technique has been recommended (Benoit, Lamontagne, Cerulli, & Liti, 2003; Burden, Trew, & Baltzopoulos, 2003; Yang & Winter, 1984) but a transient peak could affect the normalization magnitudes. However, all EMG data for all muscles for all trials were visually screened and no obvious outliers were seen. In addition, the EMG data were filtered, which reduces the effect of outliers.

4.3. Interpretation

The difference in symmetry between the components of movement has been noted previously by Winter, where he evaluated the kinematic and kinetic patterns in human gait and concluded that highly variable joint moments at the hip and knee could still produce identical joint angle patterns (Winter, 1984). The notion that many kinetic patterns are capable of producing identical kinematic patterns is supported by the theory of degrees of freedom.

The human body is a complex system with many more degrees of freedom than required to perform most tasks. The central nervous system is constantly confronted with the problem of choosing from an infinite number of possible motor strategies to achieve a motion goal (Latash, 2012). These redundant degrees of freedom are considered useful, even vital, for many aspects of motor behavior (Gorniak, Feldman, & Latash, 2009; Mattos, Latash, Park, Kuhl, & Scholz, 2011; Zhang, Scholz, Zatsiorsky, & Latash, 2008). The noticeable variability at the muscle activity and the kinetic components of movement conform to the uncontrolled manifold (UCM) hypothesis. The UCM hypothesis states that the desired movement by a system with redundant degrees of freedom is expressed as a subspace (UCM) of all possible movement choices (Latash, 2012). Further, variance along the UCM does not affect performance and is "good" variance (Latash, 2012). In fact, good variance helps an abundant system deal with secondary tasks (Zhang et al., 2008) and unexpected perturbations (Gorniak et al., 2009; Mattos et al., 2011). On the other hand, any variance orthogonal to the UCM is seen as "bad" variance and is not productive or helpful variance (Latash, 2012).

Referring to Fig. 3, the comparison between the right and left variables at each component of movement can be analyzed with the UCM hypothesis in mind. In these subplots, the black diagonal line in each subplot represents perfect symmetry between the left and right sides during the squat. The ellipse represents the best fit for the data points in each of the subplots. The long axis of the ellipse represents the range of outcomes values, known as good variance, and runs along the black diagonal line, indicative of symmetric behaviour between the right and left variables. The short axis of the ellipse, orthogonal to the UCM and long axis, indicates bad variance, or a difference in measures between the right and left sides. Noticeably, the short axis of the ellipse is smallest in the first row of subplots, indicating minimal deviation from symmetric behaviour at the kinematic component. However, the ellipse is bigger in the second and last rows of subplots, suggesting an increase in asymmetric behaviour at the kinetic and muscle activity components. To summarize, these results suggest that asymmetric movement patterns are more noticeable at the kinetic and muscle activity components, as depicted by the increased in data orthogonal to the line of symmetry.

4.4. Integration and implications

Movement quality screening tests use kinematic observation in evaluating a motion's risk profile and identify movement faults that hamper performance (Frost, Andersen, et al., 2013; Gamble, 2014; McGill et al., 2012; van Dijk et al., 2017; Whittaker et al., 2017). The findings from this study show that even when executing a highly constrained motion such as the parallel squat, there is a disconnect between the kinematic component of movement and the underlying kinetic and muscle activity components. These results suggest that current movement quality screening tests may not be capturing one's movement abilities fully and may be missing important underlying faulty movement patterns not seen using kinematic observation alone. It would be interesting to apply this multi-level component approach when assessing movement quality to determine acceptable thresholds of symmetry in movement patterns at the underlying components of movement. Furthermore, it would be interesting to apply a multi-level approach when evaluating movement quality in a clinical setting, where individuals are recovering from injury. It would be beneficial to identify and correct any compensatory mechanisms or underlying asymmetries during the rehabilitation process in order to reduce the risk of injury.

4.5. Conclusion

The results from this study suggest a disconnect between the kinematic, kinetic, and muscle activity components when evaluating movement symmetry. The findings reveal that the kinematic component shows the highest measure of symmetry, and the kinetic and muscle activity components both show reduced symmetry measures, with the muscle activity component being less symmetric than the kinetic component. The disconnect between the components of movement suggests that when evaluating movement quality, one should not rely exclusively on kinematics and observation of movement to identify movement faults.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declarations of interest

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.01.003.

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