Three-Dimensional Knee Joint Moments During Performance of the Bodyweight Squat: Effects of Stance Width and Foot Rotation

Sivan Almosnino,1,2 David Kingston,1 and Ryan B. Graham1
1Queen's University; 2Queen's University & Kingston General Hospital

The purpose of this investigation was to assess the effects of stance width and foot rotation angle on three-dimensional knee joint moments during bodyweight squat performance. Twenty-eight participants performed 8 repetitions in 4 conditions differing in stance or foot rotation positions. Knee joint moment waveforms were subjected to principal component analysis. Results indicated that increasing stance width resulted in a larger knee flexion moment magnitude, as well as larger and phase-shifted adduction moment waveforms. The knee's internal rotation moment magnitude was significantly reduced with external foot rotation only under the wide stance condition. Moreover, squat performance with a wide stance and externally rotated feet resulted in a flattening of the internal rotation moment waveform during the middle portion of the movement. However, it is speculated that the differences observed across conditions are not of clinical relevance for young, healthy participants.

Keywords: three-dimensional, inverse dynamics, waveform, principal component analysis

The bodyweight squat is prescribed in athletic and rehabilitation settings, where it is used for both training and evaluation of movement competency (Butler, et al., 2010; Kiesel, et al., 2007; Kritz, et al., 2009). The attractiveness of this exercise lies in the fact that no specialized equipment is required for performance, the physical space necessary for carrying out the movement is relatively small, the exercise resembles the performance of several everyday tasks (Schoenfeld, 2010), and several simple modifications may be made to affect training dosage and intensity.

Although the squat is a multijoint movement involving the recruitment of several muscle groups (Flanagan et al., 2003; Gullett et al., 2009; Schoenfeld, 2010), much of the literature pertaining to the biomechanical description of the exercise is concerned with alterations to knee joint mechanics and associated muscular activity (Escamilla, 2001a). In this respect, particular attention has been paid to modifications of the initial stance width and foot rotation angle adopted by the trainee (Boyden, et al., 2000; Escamilla et al., 2001b,c; McCaw & Melrose, 1999; Ninos et al., 1997; Paoli et al., 2009; Singorile et al., 1995). However, the majority of investigations concerned with quantifying the effects of the aforementioned modifications on knee kinetics have primarily used two-dimensional sagittal analyses, with the efforts themselves performed with various magnitudes of external resistance. As such, there appears to be a lack of information regarding three-dimensional (3D) knee joint moments during performance of the bodyweight squat, with specific reference to the effects of exercise modifications on external demands about any of the knee joint’s axes of rotation. Such information may be useful for optimal exercise prescription, as knowledge of which modifications result in higher moments would allow trainers to make educated decisions as to which modification to recommend as a function of a trainee’s health and training status.

Considering the lack of information related to 3D knee joint moments during performance of the bodyweight squat in general and specifically with regards to altering initial stance width or foot rotation, a study aimed at quantifying possible effects should be considered exploratory. A suitable statistical procedure to be used in this case is Principal Component Analysis (PCA). The favorable use of PCA for exploratory purposes stems from two underlying characteristics of the procedure. The first is that calculations use data of the entire moment waveform, and thus essential waveform characteristics that may contribute to the variance between conditions are not overlooked, which may occur if a-priori discrete-time
point variables are subjectively chosen for extraction (Astephen & Deluzio, 2009; Deluzio et al., 1999; Wrigley et al., 2006). The second is that, in human movement related research, it seems that the majority of the variance between conditions is usually contained within the first few principal components (PCs). This allows for a substantial reduction in the amount of data that may be further explored (Deluzio et al., 1997; Reid et al., 2010).

The purpose of this investigation was thus to assess, using an exploratory approach, the effects of stance width and foot rotation angle on three-dimensional knee joint moments during performance of the bodyweight squat exercise.

Methods

Participants

A convenience sample was recruited through direct contact and advertisements posted within the university. Potential participants were screened using a self-report medical questionnaire aimed at identifying any previous injuries to the lower extremities or spine; none of the participants were excluded. The sample consisted of 28 individuals (17 men: age 23 ± 4 years; mass 82 ± 15 kg; height 178 ± 8 cm; and 11 women: age 24 ± 6 years; mass 65 ± 10 kg; height 167 ± 9 cm). On average, the participants were involved in 6.6 ± 3.5 weekly hours of physical activity in a variety of individual and team sports at the recreational or competitive university level. All participants used the squat exercise as part of their regular exercise routines. Procedures for this investigation were approved by the University’s General Research Ethics Board, and written informed consent was obtained from all participants before testing.

Instrumentation

Three-dimensional kinematic data of the participant’s dominant leg, pelvis, and trunk were obtained using a two-camera, Optotrak 3020 motion capture system (Northern Digital, Waterloo, ON, Canada) sampling at 100 Hz. Marker clusters containing three non-collinear infrared light-emitting diodes affixed to small rigid plates were attached to the dorsal aspect of the foot using a fin that was secured to the shoe using the shoelaces and tape; the distal lateral aspect of the shank two inches above the lateral malleolus and to the thigh approximately two inches above the lateral epicondyle, both using flexible neoprene bands; and to the sacrum and trunk at the level of the T-12 vertebra using custom designed fins and flexible bands. A digitizing pointed probe fitted with a cluster of six markers was used to obtain virtual markers from the 1st metatarsal head, 5th metatarsal head, right and left malleoli, right and left femoral epicondyles, and right and left anterior superior iliac spines. These virtual markers were later used to define joint center of rotations and anatomical coordinate systems. During trial performance, ground reaction force and moment data were obtained from a strain gauge force platform embedded in the floor (model OR5–7-1000, AMTI, Watertown, MA, USA). Force plate data were sampled at 1000 Hz, and synchronized with kinematic data recordings using a 16 channel Optrak Digital Acquisition Unit (ODAU).

Procedures

Participants performed 4 squat conditions differing in either stance width or foot rotation angle: 1) Shoulder width parallel (SWP): assuming a shoulder width stance with the feet parallel to the long axis of the force plate; 2) Shoulder width rotated (SWR): assuming a shoulder width stance with feet externally rotated 30° with respect to the long axis of the force plate; 3) Wide stance parallel (WSP): assuming a stance of 140% shoulder width with feet parallel to the long axis of the force plate, and; 4) Wide stance rotated (WSR): assuming a stance of 140% shoulder width with the feet externally rotated by 30°. To replicate the starting positions between trials, stance width and foot rotation orientations were guided using adhesive tape that was placed on the floor (for the untested leg), and on the force plate (for the tested leg). For all conditions, the participants were instructed to keep their heels in contact with the ground at all times; to squat to a depth such that their inguinal fold was at the same level as the superior aspect of their knee (Fry et al., 2003); to keep their trunk straight and at a constant angle with relationship to the horizontal throughout performance; to keep the knees in line with the feet (i.e., not to bend the knees into varus or valgus) and to maintain the anterior aspect of the knee behind the toe line; to cross the arms such that the hands are touching the contra lateral shoulders; and to keep the head in a neutral and constant position (Kritz et al., 2009). A single examiner observed all squat performances, and in the case of any deviations from the predefined movement requirements, the trial was repeated. Movement time across conditions was controlled using an examiner count superimposed on a recording of a digital metronome set to 88 beats per minute (provided in supplementary audio file). The participant performed 4 randomized sets of 8 repetitions in each condition for a total of 32 trials. Within each set, trials were separated by 10 s, while a 2-min rest period was given in between sets. To eliminate fatigue as a potential confounder, a Borg 6–20 rating of perceived exertion (RPE) scale was administered after each repetition (Borg, 1982). If the participant indicated an RPE score that was a minimum of 2 scores above the one indicated for the initial trial, an additional rest period was given before the performance of the next repetition. The length of this additional rest period corresponded to the time needed for the participant to self-report full recovery. It should be noted that only two subjects required additional rest on a single occasion.

Data Analysis

Before calculations, kinematic data were filtered using a zero-phase, 4th order, low pass recursive Butterworth filter with varying cutoff frequencies ranging from 5 to
For force plate data, DC bias was removed utilizing an unweighted force plate trial. Joint centers of rotation for the ankle and knee joints were defined as the midpoint between the medial and lateral malleoli and epicondyle, respectively (Brandon and Deluzio, 2010). The hip joint center was defined using a functional method (Camomilla et al., 2006; Gamage & Lasenby, 2002). Three segmental anatomical coordinate systems were subsequently established: The femur anatomical coordinate system was defined based on the hip joint center, the knee joint center and the lateral epicondyle. The tibia anatomical coordinate system was defined by the knee joint center, the ankle joint center and lateral malleolus. The foot anatomical coordinate system was constructed with the ankle joint center, the calcaneus, and the midpoint of the 1st and 5th metatarsals. For each anatomical coordinate system, x-axis was defined to point from the distal end to the proximal end of the body segment, y-axis was defined to point along the anterior direction of the body segment, and the z-axis was defined to point in the medial direction of the body segment. Following, three-dimensional joint angles were calculated using a ZYX Euler rotation sequence; corresponding to flexion-adduction-internal rotation. In addition, 3D segmental trunk angles were also extracted. Knee joint angles and trunk orientation were referenced to a static standing trial.

Next, instantaneous net external knee joint moments were calculated using inverse dynamics procedures. For calculation purposes, the model used ground reaction forces and moments, sex-based segmental inertial characteristics (Zatsiorsky, 2002), and segmental displacement, velocity and acceleration data. In the joint moment sign convention, knee flexion, adduction, and internal rotation are defined as positive. Movement start and end periods were defined when the sagittal plane knee angle exceeded and fell below 3 SD of baseline level for a period of 200 ms, and each repetition’s start and end periods were verified by visual inspection by a single examiner. All moment waveforms were amplitude-normalized to the product of the participant’s body weight (kg) and height (m). In addition, each individual repetition period was interpolated using cubic splines to a uniform length of 201 data points, which represented 0–100% of the movement phase in 0.5% increments. All analyses were performed using Matlab version 7.5 (The Mathworks, Natick, MA, USA).

**Statistical Analysis**

Representative moment waveforms for each participant in each condition were attained by ensemble averaging across trials. These waveforms were subsequently subjected to Principal Component Analysis (PCA). Procedures for PCA implementation for waveform analyses are detailed elsewhere (Astephen & Deluzio, 2009; Deluzio & Astephen, 2007; Deluzio et al., 1999; Wrigley et al., 2006). For data reduction purposes, the number of PCs retained for further analysis was determined using a 90% trace criterion (Reid et al., 2010). Subsequently, differences in PC scores between conditions were assessed using a 2-way, repeated-measures analysis of variance (ANOVA), with the within-participant factors being stance width and foot rotation. The alpha level for these comparisons was preset at 0.05 with Bonferroni adjustment to account for multiple comparisons. Complementary effect size estimates are reported using generalized omega squared ($\omega^2$) for repeated measures experimental design (Olejnik & Algina, 2003).

For interpretation of the results of those PCs found to statistically differ across conditions, two approaches were used: 1) inspection of associated loading vector plots, and 2) inspection of plots of the mean temporal waveform across all conditions, bounded by the contribution of a single PC pattern of variance, which in turn, is scaled by one standard deviation of the group PC-scores (Brandon et al., 2013; Ramsay & Silverman, 1997; O’Connor & Bottum, 2009). This latter technique differs from common method of examination of extreme score subject waveforms (e.g., Astephen & Deluzio, 2009; Reid et al., 2010) in that the variance contributions of other PCs to the representative waveforms being examined are omitted (Brandon et al., 2011; Ramsay & Silverman, 1997).

In addition, three separate one-way repeated-measures ANOVAs were conducted to discern any differences in average 3D trunk orientation across conditions ($\alpha = .05$).

Lastly, to assess whether PCA offers any advantages over conventional moment waveform analysis, the relative absolute impulse (RIMP; absolute area under the amplitude and time-normalized moment curve) was extracted from each participants’ ensemble averaged joint moment curve in each squat condition (Hamill et al., 1983). The choice to extract RIMP as a representative measure was due to the fact that the calculation utilizes data of the entire waveform, and hence is similar in this respect to PCA. In addition, the choice of RIMP is in line with the aim of the investigation, namely to assess the influence of certain modifications on external demands about the knee joint throughout the entire movement cycle. Furthermore, the strength of the associations between absolute peak moment and RIMP values were quite strong ($r^2 = .67$, .82, and .88 for the association between peak and relative impulse for flexion moment, abduction moment, and internal rotation moment components, respectively), and as such reporting of peak values would be inherently redundant. 2-way repeated-measures ANOVAs were used to assess the influence of the two within-participant factors on RIMP values, with alpha preset at 0.05.

**Results**

Principal component models were produced for the knee joint moment data (Figure 1) and a total of $10$ PC’s were retained utilizing the 90% trace criterion (Table 1). Of these, only $5$ PC’s were statistically significant ($p \leq .001$). The interpretation of these PC’s was achieved via examination of Figure 2; consisting of loading vectors, ensemble mean waveforms bounded by $\pm 1$ SD single PC variance patterns, and interaction plots.
Figure 1 — Three-dimensional bodyweight and height normalized net external knee joint moments during performance of the bodyweight squat in each of the four conditions. Data are presented as group mean ± SD.
Figure 2 — Principal component analysis results of 3D knee joint moment waveforms. 1st row: Group mean moment waveform for each condition in which statistical significance was detected. 2nd row: Loading vector plots of the PC of interest. 3rd row: Ensemble moment curve across all conditions ± 1 SD of the variation due to the PC loading vector shown in the 2nd row. 4th row: Interaction plots.
<table>
<thead>
<tr>
<th>Knee Moment Component and PC #</th>
<th>Explained Variance (%)</th>
<th>SWP</th>
<th>SWR</th>
<th>WSP</th>
<th>WSR</th>
<th>Stance Width Main Effect (p value)</th>
<th>Foot Rotation Main Effect (p value)</th>
<th>Stance Width × Foot Rotation Interaction (p value)</th>
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<tbody>
<tr>
<td>Flexion/Extension</td>
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<tr>
<td>1</td>
<td>67.9</td>
<td>-0.65 ± 1.67</td>
<td>0.68 ± 1.34</td>
<td>-0.45 ± 1.37</td>
<td>0.4 ± 1.3</td>
<td>0.841</td>
<td>&lt; 0.0001</td>
<td>0.032</td>
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<td>13.9</td>
<td>0.10 ± 0.68</td>
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<td>0.198</td>
<td>0.176</td>
<td>0.804</td>
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<td>3</td>
<td>8.9</td>
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<td>0.15 ± 0.48</td>
<td>-0.29 ± 0.70</td>
<td>0.08 ± 0.59</td>
<td>0.090</td>
<td>0.016</td>
<td>0.018</td>
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<td>Adduction/Abduction</td>
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<tr>
<td>1</td>
<td>58.6</td>
<td>0.13 ± 0.65</td>
<td>0.13 ± 0.81</td>
<td>0.02 ± 0.71</td>
<td>-0.29 ± 0.81</td>
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<td>0.180</td>
<td>0.011</td>
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<td>20.5</td>
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<td>-0.13 ± 0.47</td>
<td>0.14 ± 0.41</td>
<td>0.03 ± 0.41</td>
<td>&lt; 0.0001</td>
<td>0.116</td>
<td>0.780</td>
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<td>0.02 ± 0.33</td>
<td>-0.01 ± 0.32</td>
<td>-0.06 ± 0.36</td>
<td>0.017</td>
<td>0.207</td>
<td>0.808</td>
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<tr>
<td>4</td>
<td>5.0</td>
<td>0.00 ± 0.23</td>
<td>0.07 ± 0.18</td>
<td>-0.03 ± 0.25</td>
<td>-0.05 ± 0.22</td>
<td>0.014</td>
<td>0.336</td>
<td>0.073</td>
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<tr>
<td>1</td>
<td>82.8</td>
<td>0.02 ± 0.56</td>
<td>0.02 ± 0.53</td>
<td>-0.11 ± 0.60</td>
<td>0.07 ± 0.50</td>
<td>0.182</td>
<td>0.153</td>
<td>0.001</td>
</tr>
<tr>
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<td>6.9</td>
<td>-0.02 ± 0.13</td>
<td>0.01 ± 0.17</td>
<td>-0.01 ± 0.17</td>
<td>0.02 ± 0.16</td>
<td>0.381</td>
<td>0.017</td>
<td>0.740</td>
</tr>
<tr>
<td>3</td>
<td>6.0</td>
<td>0.00 ± 0.12</td>
<td>0.04 ± 0.16</td>
<td>0.00 ± 0.14</td>
<td>-0.04 ± 0.16</td>
<td>0.02</td>
<td>0.87</td>
<td>0.001</td>
</tr>
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</table>

Note. Initial Squat Conditions: SWP = Shoulder width stance, feet parallel to the long axis of the force plate, SWR = Shoulder width stance, feet rotated 30°, WSP = Stance of 140% of shoulder width, feet parallel to the long axis of the force plate, WSR = Stance of 140% of shoulder width, feet rotated 30°.
A significant main effect of foot rotation is noted for PC1 of the knee flexion moment ($\omega^2 = 0.31$). The magnitude of the corresponding loading vector is positive throughout the entire cycle, with two conspicuous peaks at approximately 35% and 55% of the cycle, signifying an increased variability between the parallel and foot rotated conditions at these instances. Supported by examination of the single PC reconstructed plot; this PC is interpreted as a measure of overall magnitude difference between the parallel and foot rotated conditions, with foot rotation significantly increasing overall flexion moment magnitude.

With regards to the adduction moment, no effect of foot rotation was noted across conditions. However, a wide stance resulted in significantly lower adduction moment PC1 and PC2 scores ($\omega^2 = 0.18$ and 0.19, respectively). A lower adduction moment PC1 score indicates a larger adduction moment range. In addition, it is evident that in the initial and last thirds of the movement cycle, those with a low PC1 score experience a knee adduction moment, while in the middle third of the cycle, these participants experience an abduction moment. Conversely, those with high PC1 scores tend to experience an abduction moment in the initial and final 20% of the cycle, while in the 60% of the cycle a conspicuous double peak occurs with the moment reversing sign from adduction to abduction and back to adduction. In terms of PC2 of the adduction moment, a phase shift is noted whereby during the performance of the squat in the wide stance conditions there is a tendency to reach the peak abduction moment slightly earlier in the movement cycle.

Results for PC1 of the knee internal rotation moment reveal a significant interaction between stance width and foot rotation ($\omega^2 = 0.17$). In the wide stance and rotated feet position, internal rotation moment was of lesser magnitude throughout the entire movement cycle, in comparison with performance with parallel feet. There appears to be no difference with respect to the narrower width squat condition, irrespective of foot positioning. In addition, a significant interaction was noted for PC3 of the knee internal rotation moment ($\omega^2 = 0.165$). During squat performance with parallel feet, there appears to be no difference in the internal rotation moment. However, during performance of the wide stance with the feet rotated outwards, there appears to be a flattening of the moment waveform during the middle portion of the movement phase. Conversely, during performance of the squat with a shoulder width stance and the feet rotated, the moment waveform exhibits a distinct peak approximately midcycle.

Results for relative impulse (RIMP) values obtained for each knee joint moment component during performance of the four exercise variations are summarized in Table 2. For the flexion moment, RIMP values were significantly higher when performance was done with rotated feet. These results are in agreement with both the results and interpretation of PC1 as being a magnitude operator.

With regards to the adduction moment component, performance of the exercise at a stance of 140% of shoulder width resulted in significantly higher RIMP values in comparison shoulder width stance performance. It may be argued that this finding is in agreement with the results and interpretation of adduction moment PC1 as being a range operator. However, RIMP values do not identify the alterations in moment sign throughout the movement cycle between those that scored low or high on PC1, nor are RIMP values sensitive to the phase shift identified by PC2.

Results for RIMP values obtained for the internal rotation joint moment component reveal a significant interaction between stance width and foot rotation. In specifics, during performance with a wide stance and rotated feet, RIMP was smaller than when performance was done with a wide stance and parallel feet. In addition, no differences in RIMP values were noticed when squats were performed with a shoulder width stance, regardless of the foot position employed. These results are concurrent with the interpretation of PC1 scores; however they do not reveal the subtle flattening of the moment waveform in the middle portion of the movement cycle captured by PC3.

Lastly, repeated-measures ANOVA revealed no statistically significant differences in average 3D trunk orientation across conditions ($p > .3$ for all comparisons). During the performance of each condition, the mean normalized time period where the maximum knee flexion angle was reached was NP 52.5 ± 3.5%, NR 53 ± 4%, WP 53 ± 4%, and WR 52 ± 3.5% of the total cycle, and was not statistically significant across conditions ($p = .44$).

**Discussion**

This investigation is the first to report on the 3D knee joint moment waveforms during the performance of several variants of the bodyweight squat. It should be noted that other investigations have depicted knee flexion/extension moment waveform shapes during performance of the squat exercise; however, these investigations were primarily concerned with descriptions of performance with external resistance. Disregarding expected magnitude differences between the unweighted and weighted versions of the exercise, it should be noted that there are some differences in waveform shapes. Specifically, in our investigation there is a tendency for an external knee flexion moment throughout the entire movement phase, whereas other investigations explicitly state or are presumed to be reporting an internal extensor moment at the initial and final phases of the movement (e.g., Flanagan et al., 2003; Gullett et al., 2009; Robertson, et al., 2008). This difference in waveform shape is most likely attributed to the decision regarding the movement’s start and end points. In terms of the magnitudes of the knee flexion moment, results of the current investigation are approximately 15–20% higher than those reported by Butler et al. (2010). In this latter investigation, which was concerned with analyses of the bodyweight squat, movement was performed through a full range of knee flexion (i.e., deep squat), and at a self selected pace. The
Table 2  Relative impulse (RIMP) results obtained for each knee moment component in each of the four squat conditions

<table>
<thead>
<tr>
<th>Knee Moment Component</th>
<th>Mean ± SD, Relative Impulse</th>
<th>Stance Width Main Effect (p value)</th>
<th>Foot Rotation Main Effect (p value)</th>
<th>Stance Width × Foot Rotation Interaction (p value)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SWP</td>
<td>SWR</td>
<td>WSP</td>
<td>WSR</td>
</tr>
<tr>
<td>Flexion/Extension</td>
<td>45.92 ± 8.55</td>
<td>54.50 ± 10.69</td>
<td>47.48 ± 9.02</td>
<td>53.63 ± 8.69</td>
</tr>
<tr>
<td>Adduction/Abduction</td>
<td>5.86 ± 3.00</td>
<td>6.37 ± 3.37</td>
<td>6.53 ± 3.45</td>
<td>7.98 ± 3.66</td>
</tr>
<tr>
<td>Internal/External Rotation</td>
<td>10.99 ± 3.37</td>
<td>10.85 ± 3.20</td>
<td>11.92 ± 3.60</td>
<td>10.63 ± 3.01</td>
</tr>
</tbody>
</table>

Note. Initial Squat Conditions: SWP = Shoulder width stance, feet parallel to the long axis of the force plate, SWR = Shoulder width stance, feet rotated 30°, WSP = Stance of 140% of shoulder width, feet parallel to the long axis of the force plate, WSR = Stance of 140% of shoulder width, feet rotated 30°.
latter has been shown to influence values of inputs serving inverse dynamics calculations (Bentley et al., 2010), and as such is likely to explain the differences in results. We are aware of only one other investigation that has characterized knee adduction and internal rotation moments during performance of a bodyweight squat (Faber et al., 2010, moments in this investigation are presumed to be reported as internal), and in this investigation movement was performed with the intention of lifting a wide 10-kg box from floor level. Therefore, waveform shapes cannot be readily compared. However, it seems that if considering only the unloaded descent phase in this latter study, than moment magnitudes are fairly similar to the unnormalized magnitudes obtained in our investigation (not reported).

With regards to the differences observed across stance width and foot rotation conditions in the current investigation; it is unclear whether these are of clinical significance specifically for enhancing knee musculature conditioning. If relying on interpretation of effect size estimates, then the differences observed across conditions may be considered small. It is interesting to note in this respect that previous investigations concerned with assessment of superficial thigh musculature activity during weighted squat exercise with either different stance widths or foot rotations have, in general, not found differences across conditions (Boyden et al., 2000; McCaw & Melrose, 1999; Paoli et al., 2009; Singorile et al., 1995). If extrapolating these latter findings to the current investigation, then our interpretation regarding the insignificance of the proposed modifications for enhancing aspects of thigh musculature conditioning is supported. Given this, it seems that trainees may adopt the stance width and foot rotation angle that they perceive to be most comfortable during performance. Incidentally, informal questioning of our participants following testing revealed that out of the four stance widths and foot rotation variations, the majority preferred performing the exercise within a shoulder width stance and feet rotated outwards by 30°.

It should be noted that there are other possible modifications that can be made to the bodyweight squat exercise to potentially affect training intensity and dosage. Some of these modifications have been assessed to some degree during performance of the weighted squat exercise, including the effects of squat depth (Caterisano et al., 2002) and cadence (Hattin, et al., 1989). Given the lack of information on the matter with regards to the bodyweight squat, examining such effects in future investigations would be of interest.

Several limitations of the current investigation should be noted. First, knee joint kinematic values are prone to errors resulting from misalignment of the joint coordinate system with the axes about which rotation actually occurs (Piazza & Cavanagh, 2000). As kinematics serve as inputs for inverse dynamics calculations, an error in axes alignment may inherently influence the shape and magnitude of resulting knee joint moments. In this investigation, a single and experienced examiner performed palpation of the anatomical landmarks used as virtual markers, as this would eliminate interexaminer discrepancies. In addition, the vast majority of the participants in this investigation may be characterized as lean individuals, which aided in locating the aforementioned anatomical landmarks. In any case, as this is the first investigation to depict 3D moment waveforms during the bodyweight squat, we encourage validation of results by others. In addition, although the use of PCA in this investigation enabled objective extraction of joint moment waveform features that would not have been recognized if a parameter based analysis was used; the interpretation of these features is nevertheless subjective. As noted previously, the current method of interpretation using the single reconstructed PC plots appears to offer some advantages with respect to the more common method of extreme waveform evaluation (Brandon et al., 2013).

In conclusion, this investigation provides a description of 3D knee joint moment waveforms during variations of the bodyweight squat exercise. These variations, which involved modifications of the initial stance width and foot rotation angle, seem to have only a minor and perhaps clinically irrelevant effect with regards to exercise demands. Practically, the findings suggest that healthy participants may adopt a squat position that is most comfortable for performance. Future research directions that may be of interest involve the effects of other possible bodyweight squat modifications on knee joint moments, as well as expanding to investigations of the version of the exercise commonly performed with external resistance.

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References


