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Can hip and knee kinematics be improved by eliminating thigh markers?

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Abstract

Background—Marker sets developed for gait analysis are often applied to more dynamic tasks with little or no validation, despite known complications of soft tissue artifact.

Methods—This study presents a comparison of hip and knee kinematics as calculated by five concurrently-worn tracking marker sets during eight different tasks. The first three marker sets were based on Helen Hayes but used 1) proximal thigh wands, 2) distal thigh wands, and 3) patellar markers instead of thigh wands. The remaining two marker sets used rigid clusters on the 4) thighs and shanks and 5) only shanks. Pelvis and foot segments were shared by all marker sets. The first three tasks were maximal femoral rotations using different knee and hip positions to quantify the ability of each marker set to capture this motion. The remaining five tasks were walking, walking a 1m radius circle, running, jumping, and lunging.

Findings—In general, few and small differences in knee and hip flexion-extension were observed between marker sets, while many and large differences in adduction-abduction and external-internal rotations were observed. The shank-only tracking marker set was capable of detecting the greatest hip external-internal rotation, yet only did so during dynamic tasks where greater hip axial motions would be expected. All data are available as supplementary material.

Interpretation—Marker set selection is critical to non-sagittal hip and knee motions. The shank-only tracking marker set presented here is a viable alternative that may improve knee and hip kinematics by eliminating errors from thigh soft tissue artifact.

Keywords

Biomechanics; motion analysis; soft tissue artifact (STA); marker sets; kinematics; stereophotogrammetry; hip; knee; gait; running; turning; jumping; lunging

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Conflict of interest statement

None of the authors have any financial or personal relationships with any people or organizations that could benefit from or bias this work in any way.

1. Introduction

Various forms of the Helen Hayes marker set dominate clinical gait analysis and are still used extensively for research despite their known limitations (Schache et al., 2008; Wren et al., 2008; Karlsson and Tranberg, 1999). These limitations include the use of joint markers at the knee despite these markers being subject to substantial soft tissue artifact (STA) of up to 40mm (Cappozzo et al., 1996; Karlsson and Tranberg, 1999) and its use of thigh wands or markers that capture approximately half of actual femoral axial rotation (Schache et al., 2008; Wren et al., 2008). Recent studies have replaced the thigh marker or wand with a marker on the patella, which has been shown to be capable of detecting up to 98% of femoral axial motion (Wren et al., 2008) and be less subject to offsets in femoral axial rotation profiles due to differences in static calibration position (McMulkin and Gordon, 2009). While this appears promising and may be an adequate solution for clinical gait analysis, patellar markers are likely to be subject to similar STA errors as lateral knee markers. Furthermore, we are unaware of any validation for this method for more dynamic tasks incorporating greater knee flexion, where patellar motion beneath this marker may induce additional errors.

Cluster-based marker sets are a proposed solution to some of these issues. Rigid or deformable marker clusters are generally not located near joints and thus avoid this source of error. However, all non-invasive marker sets (save the patellar marker exception) require individual markers or clusters to be affixed to the thigh. These markers are subjected to substantial STA, especially when placed proximally where the greatest STA of any lower-limb segment is found (Stagni et al., 2005).

To address these issues and present another possible solution to the shortcomings of the Helen Hayes marker set, this paper presents a comparison of five different tracking marker sets recorded simultaneously during eight different tasks.

2. Methods

2.1. Subject and instrumentation

A 13-camera Vicon MX-40 system (Vicon, Centennial, CO, USA) was used to track the motion of 36 15mm retroreflective markers on a single unimpaired male experimenter (height=1.7m, mass=84kg). All foot (lateral malleolus, calcaneus, and 2nd metatarsophalangeal joint) and pelvis (anterior superior iliac spines and posterior superior iliac spines) markers were common to all marker sets tested. All joint centers, axes, and segment local coordinate systems were also common to all marker sets. The hip joint centers were determined as per regression methods of Davis et al. (1991), the knee and ankle joint axes were defined by medial (present only in static trial) and lateral joint markers, and the knee and ankle joint centers were defined as the midpoints of these markers.

The five tracking marker sets used to record thigh and shank motion were 1) Helen Hayes using proximally-affixed thigh wands (HHprox), 2) Helen Hayes using distally-affixed thigh wands (HHdist), 3) Helen Hayes using patellar markers instead of thigh wands (HHpat), 4) rigid four-marker shank and thigh clusters (C-ST), and 5) rigid shank clusters only (C-S).

All markers and clusters were adhered to the skin and wrapped with SuperWrap (Fabrifoam, Exton, PA, USA). Thigh clusters were affixed mid-thigh between the proximal and distal thigh wands.

The shank-only marker set (C-S) was developed for the lunging task where pilot testing has indicated that substantial knee and hip flexions may exacerbate STA for thigh-mounted markers. While cluster-based marker sets (e.g. C-ST) typically locate joint centers and axes using the proximal segment cluster, C-S completely circumvents thigh STA by locating both the knee and ankle joint centers and axes relative to the shank cluster and eliminating the thigh cluster. Since shank STA is at a minimum on the tibial crest (Peters et al., 2009), novel shank clusters were affixed here rather than the typical lateral placement. This lower body marker set is conceptually similar to the upper-body marker set proposed by Rab et al. (2002), but tracks the shank segments using central rigid clusters rather than discrete skin-mounted joint markers that are less likely to remain stationary with respect to the underlying skeletal anatomy (Karlsson and Tranberg, 1999; Peters et al., 2009). Analogous to shoulder angles in Rab et al. (2002), hip flexion-extension and adduction-abduction were defined by the position of the thigh relative to the pelvis, and hip internal-external rotation was defined by the position of the knee flexion-extension axis relative to the thigh. This allows hip motion to be tracked without the use of thigh markers, but as a consequence one knee degree-of-freedom (DOF) is shared between adduction-abduction and external internal rotation. That is, as the knee approaches full extension, knee external-internal rotation approaches zero and adduction-abduction is accurately captured. Conversely, as the knee approaches 90° of flexion, knee adduction-abduction rotation approaches the value from the static trial and external-internal is accurately captured.

2.2. Testing protocol

All eight tasks were performed barefoot and ten trials of each were recorded. The first three tasks consisted of three repetitions of maximal active hip external-internal rotations to evaluate the extent of femoral axial rotation captured by each marker set. The first of these was performed with the knee at full extension and almost completely unloaded (heel just contacting ground) to minimize knee motion. For the second of these tasks, the knee was completely unloaded and flexed to approximately 90°. For the third task the hip was additionally flexed to ~90°.

The remaining five tasks were 4) habitual speed walking along a straight path (walking), 5) habitual speed walking in two clockwise or counterclockwise circuits of a 1m radius circle (turning)- five trials in each direction, 6) running along a straight path (running), 7) maximal height jumping (jumping), and 8) maximal length out-and-back lunging (lunging)- five trials for each leg (Medell and N.B. Alexander, 2000; Schulz et al., 2008; Schulz et al., 2007). Gait cycles were analyzed from initial contact to initial contact, jumping was analyzed over “liftoff” (beginning of crouch to liftoff) and “landing” (ground contact to maximal knee flexion) phases, and lunging was analyzed over the “pushback” phase (initial contact of step out to liftoff of return step). The asymmetrical tasks were also broken down by side (i.e. turning examined by inside vs. outside leg and lunging examined by stepping vs. stance legs).

2.3. Data processing and analysis

All data were collected and preprocessed using Vicon Workstation. All postprocessing, analysis, and plotting was completed using Visual3D (C-Motion, Germantown, MD, USA). The generalized six degree-of-freedom modeling technique (no global optimization) was utilized and joint motions were defined using the floating axis convention of Grood and Suntay (1983). Only knee and hip joint angle data were examined here. Descriptive analyses of triaxial knee and hip motions were analyzed for only the left leg to eliminate any variability caused by right-left differences. The non-sagittal range of motions (ROMs) for all tasks were presented as a bar plot summary and walking, inside leg turning, and stepping leg lunging angles were plotted with respect to task cycle here, but all plots and data are available as supplementary material online.

Results

3.1. Femoral axial rotation tasks

C-S captured the greatest femoral axial rotations for these three tasks ($70 \pm 8^\circ$ for knee locked, $73 \pm 3^\circ$ for only knee flexed, and $58 \pm 5^\circ$ for knee and hip flexed, Fig. 1). Greater hip axial rotations were captured with the hip neutral (mean across all marker sets when knee locked = $50 \pm 6^\circ$ and $51 \pm 4^\circ$ when knee flexed) than with the hip flexed ($35 \pm 5^\circ$). When C-S was used as the standard of comparison (i.e. 100%), all marker sets using thigh markers captured approximately half of the motion captured by C-S (HHprox = $42 \pm 7\%$, HHdist = $50 \pm 7\%$, C-ST = $52 \pm 7\%$) while HHpat captured $93 \pm 9\%$. At the knee, all but C-S captured over 20° of non-sagittal ROM (Fig. 1).

3.2. Dynamic tasks

Considering the quantity of data examined here, summarized and representative results are presented, but all data and plots are available online. Few and small differences in flexion-extension motions and hip adduction-abduction were observed between marker sets, aside from a general offset of C-ST towards greater hip adduction. However, many and large differences in knee adduction-abduction and both hip and knee external-internal rotations were observed (Figs. 1–4). While these data are summarized by ROM here (Fig. 1), this does not capture the complete extent of the differences. These joint angle traces are frequently quite different in both shape and/or mean value (Figs. 2–4).

At the hip, C-S generally calculated similar or greater external-internal rotations than the other marker sets evaluated. The main exception to this was running, where HHprox & HHdist calculated nearly twice as much external-internal rotation ROM as the other three marker sets (Fig. 1). At the knee, C-S captured less non-sagittal ROM than all other marker sets (Fig. 1).

Discussion

Depending on specific task, joint, and motion, large differences between marker sets were found. The femoral rotation test results were consistent with prior studies (Schache et al., 2008; Wren et al., 2008) and demonstrated that more distal markers were generally capable

of capturing greater external-internal hip motions with C-S capturing the most. The reason for this may be that substantial proportions of hip external-internal rotations were being detected as knee motions by the marker sets using thigh markers (HHprox, HHdist, and C-ST). For example, C-S captured 28–41° (68–242%) more femoral axial rotation than these marker sets, but when the hip external-internal rotation ROM was added to the knee external-internal rotation ROM for the first task (knee locked) and to the knee adduction-abduction ROM for the second and third tasks (knee flexed to ~90°), the combined ROMs for all five marker sets were within 4.1°, 2.1°, and 2.8° of each other for three hip rotation tasks. These values are all less than the mean standard deviation for hip external-internal rotation ROM for all marker sets during the three hip rotation tasks (5°). The consistency of this combined knee and hip ROM across marker sets for the hip rotation tasks supports the hypothesis that substantial hip external-internal rotations are being detected at the knee by marker sets using thigh markers.

The femoral rotation tasks demonstrated that C-S was capable of capturing up to 242% more external-internal hip rotation ROM than the other tracking marker sets evaluated, but for the other dynamic tasks C-S only detected substantially more for tasks (e.g. turning, jumping, & lunging) that would be expected to elicit greater external-internal rotations. C-S actually captured substantially less external-internal rotation ROM than HHprox and HHdist for running (Fig. 1), where thigh STA during the fast, bouncing gait pattern was likely to have artificially increased the ROM detected by thigh-mounted markers.

At the knee, all but C-S detected motions that were beyond established limits for external-internal rotation ($>33^\circ$ or $<-23^\circ$) or adduction-abduction ($>10^\circ$ or $<-10^\circ$) (Blankevoort et al., 1988). However, this study reports no ‘gold standard’ to define true skeletal motions. Considering that data from prior studies using intracortical pins have demonstrated substantial inter-subject and inter-study variation (McClay, 1990; Benoit et al., 2006; Reinschmidt et al., 1997; Reinschmidt et al., 1997; Lafortune et al., 1992; Houck et al., 2004), no conclusions regarding which marker set most accurately represents true skeletal motions can be drawn from these data.

The greatest limitation of C-S is the sharing of one knee DOF between external-internal rotation and adduction-abduction. This results in underestimation of knee external-internal rotation as the knee approaches full extension and underestimation of knee adduction-abduction as the knee approaches 90° of flexion (Fig. 5). For external-internal rotation, this property roughly corresponds to the movement permitted by the knee anatomy and to the data from Blankevoort et al. (1988). For adduction-abduction, the underestimation caused by this DOF sharing may be preferable to the substantial hip motions interpreted by marker sets using thigh markers as non-physiologic (ROM $>35^\circ$) knee adduction-abduction motion (Fig. 1). Again, comparisons a ‘gold standard’ are required to establish which marker set most closely approximates the true skeletal motions for each task.

These findings indicate that by eliminating STA from the thigh, C-S is less subject to total STA than other tracking marker sets. Eliminating markers on the thighs would also reduce set up time and the amount of instrumentation on subjects, presumably resulting in more natural gait patterns. Furthermore, if C-S was implemented via electromagnetic or inertial

six-DOF measurement systems, all lower limbs could be tracked using only five sensors rather than seven. This could substantially reduce the costs of portable gait analysis systems. We conclude that marker set selection is critical to non-sagittal hip and knee motions and that the shank-only (C-S) marker set presented here is a viable alternative that has the potential to improve knee and hip kinematics, particularly for tasks such as turning where hip external-internal rotations are anticipated and/or of interest. To answer the question posed by the title: hip external-internal rotations can be improved by eliminating thigh markers while other hip motions and knee flexion-extension are not substantially altered. If knee adduction-abduction or external-internal rotations are of interest, then we cannot recommend the use of any skin-mounted tracking marker set without further validation to a gold standard during the specific task of interest.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Figure 1.

Mean (SD) of external-internal rotation (upper row within each panel) and adduction-abduction (lower row within panel) range of motion (ROM) in degrees for hip (top panel) and knee (bottom panel) during all tasks as recorded by five tracking marker sets evaluated. Note y-axis scale differences between hip rotation tasks (three leftmost bar groups) and dynamic tasks (eight rightmost bar groups).

Figure 2.

Walking along a straight path ensemble mean data of left hip (top row) and knee (bottom row) flexion (left column), adduction (middle column), and external rotation (right column) angles for 21 habitual speed gait cycles as calculated by five tracking marker sets tested (HHprox=blue, HHdist=green, HHpat=purple, C-ST=red, C-S=black). X-axis is percentage of gait cycle with initial contact occurring at 0 and 100% and foot-off occurring as indicated by vertical line. Envelope of ± 1 SD shown only for C-S marker set for clarity (SD similar for all traces).

Figure 3.

Walking while turning counter-clockwise in a 1m radius circle ensemble mean data of left hip (top row) and knee (bottom row) flexion (left column), adduction (middle column), and external rotation (right column) angles for 40 habitual speed gait cycles as calculated by five tracking marker sets tested (HHprox=blue, HHdist=green, HHpat=purple, C-ST=red, C-S=black). X-axis is percentage of gait cycle with initial contact occurring at 0 and 100% and foot-off occurring as indicated by vertical line. Envelope of ± 1 SD shown only for C-S marker set for clarity (SD similar for all traces).

Figure 4.

Maximal length left out-and-back lunge ensemble mean data of stepping hip (top row) and knee (bottom row) flexion (left column), adduction (middle column), and external rotation (right column) angles as calculated by five tracking marker sets tested (HHprox=blue, HHdist=green, HHpat=purple, C-ST=red, C-S=black). X-axis is percentage of “pushback” cycle with initial contact of step out occurring at 0% and foot-off of return step occurring at around 100%. Envelope of ± 1 SD shown only for C-S marker set for clarity (SD similar for all traces).

Figure 5.

Phase plots of left knee adduction-abduction and external-internal rotation angles as a function of knee flexion angle during the “liftoff” phase (beginning of crouch to foot off) of ten maximal height jumps for C-S (only shank clusters) and C-ST (shank and thigh clusters) tracking marker sets. Note that C-S adduction-abduction approaches the static trial value of -5.2° at 90° flexion and external-internal rotation approaches 0° as flexion approaches at 0° due knee adduction-abduction and external-internal rotation sharing a single degree-of-freedom for the C-S tracking marker set.