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ABSTRACT

Objectives: To examine test-retest reliability of two-dimensional measured frontal and sagittal plane kinematics during running, and to determine how many steps to include to reach and maintain a stable mean.

Design: Reliability study

Setting: Research laboratory

Participants: Twenty-one recreational runners

Main Outcome Measures: Lateral trunk position, contralateral pelvic drop, femoral adduction, hip adduction, knee flexion and ankle dorsiflexion during midstance, and foot and tibia inclination at initial contact were measured with two-dimensional video analysis during running for 10 consecutive steps for both legs. All participants were tested twice one week apart. A sequential estimation method was used to determine the number of steps needed to reach a stable mean. Intraclass correlation coefficients (ICC) and smallest detectable differences (SDD) were calculated.

Results: The minimal number of steps was 6.3±0.3. Lateral trunk position, femoral adduction and foot inclination showed excellent reliability (ICC 0.90-0.99;SDD 1.3°-2.3°). Tibia inclination and ankle dorsiflexion showed good to excellent reliability (ICC 0.73-0.92;SDD 2.2°-4.8°). Hip adduction and knee flexion showed good reliability (ICC 0.82-0.89;SDD 2.3°-3.8°). Contralateral pelvic drop showed moderate to good reliability (ICC 0.59-0.77;SDD 2.7°-2.8°).

Conclusion: Two-dimensional video analysis is reliable to assess running kinematics on different days. The mean of at least 7 steps should be included.

KEYWORDS

Running, kinematics, two-dimensional video analysis, reliability

HIGHLIGHTS

At least 7 steps should be used to reach and maintain a stable mean.

Good to excellent test-retest reliability was found for 2D video analysis.

2D video analysis of running kinematics can be used confidently on different days.

INTRODUCTION

Increasing evidence supports the theory that altered lower extremity kinematics during running may be related to a broad range of outcomes such as running performance,[17] running economy[26] and running-related injuries.[1, 5, 9, 25, 27, 30, 31, 35] In addition, the ability to measure changes in lower extremity running kinematics is essential to further understand the effect of interventions. The majority of published studies reporting kinematics in runners,[1, 25, 27, 30, 31, 35] have used three-dimensional motion analysis systems, which are considered the gold standard for a detailed running analysis.[23] However, this methodology requires expensive equipment, is time-consuming and is currently not widely available in clinical settings where physical therapists or athletic trainers work with runners. Reliable, accurate and inexpensive methods that are time-efficient and user-friendly are required to facilitate the evaluation of running kinematics in clinical settings.

Pipkin et al[34] evaluated the inter- and intrarater reliability of a qualitative approach where running kinematics of 15 individuals were assessed with a visual categorical rating of two-dimensional video recordings with a high-speed camera in the frontal and sagittal plane. The intra- and interrater reliability was strongly dependent on the kinematic variable of interest. Substantial to excellent intrarater reliability was found for 11/15 kinematic outcomes, whilst this was only the case for 5/15 kinematic outcomes for the interrater reliability.

Next to the visual categorical evaluation of running kinematics, measuring angles of different joints of interest using two-dimensional video analysis might offer an alternative approach to evaluate running kinematics in clinical settings. Dingenen et al[13] recently reported a significant relationship between peak two-dimensional measured contralateral pelvic drop, femoral adduction and hip adduction, and the three-dimensional measured hip adduction kinematic profile during running. Peak two-dimensional measured contralateral pelvic drop was also significantly related to the three-dimensional measured contralateral pelvic drop kinematic profile across the majority of the stance phase. In accordance with the study of Maykut et al[23], excellent intra- and intertester reliability was found for all frontal plane angles, including contralateral pelvic drop, femoral adduction and hip adduction, when the same videos were evaluated on different days. In the sagittal plane, different kinematic outcomes resulting from two-dimensional video analysis have been reported at initial contact and midstance, such as foot inclination,[3, 34, 41, 43] tibia inclination[34, 41] and knee flexion.[8, 41] Damsted et al[8] evaluated within and between day intra- and intertester reliability of two-dimensional video measures of knee and hip flexion angles at initial contact during running. However, the magnitude of change beyond measurement error was not calculated. Therefore, the test-retest reliability of two-dimensional frontal and sagittal plane analysis when the runner is tested on different days remains unclear. This is important because assessment and re-assessment of running kinematics in a clinical setting often occur on different days.

The current limitation of unknown test-retest reliability when using two-dimensional video analysis collected on different days, as opposed to the same video being rated on different days, hampers the interpretation of changes in outcomes when retesting an individual runner. Based on the inter-session variability of running kinematics and the increasing scientific support for running retraining to treat lower limb injuries,[5] this information is essential to use two-dimensional video analysis effectively before and after interventions. Furthermore, given the intrinsic variability of human running,[19] it is not clear how many steps should be included and averaged when assessing two-dimensional measured kinematic outcomes in order to obtain stable gait data.

The purpose of this study was therefore twofold. First, we aimed to determine the minimum number of steps required to obtain a stable mean to assess two-dimensional measured running kinematics for lateral trunk position, contralateral pelvic drop, femoral adduction, hip adduction, knee flexion and ankle dorsiflexion during midstance, and foot and tibia inclination at initial contact. Second, we aimed to examine the test-retest reliability of these two-dimensional measured kinematics.

METHODS

Participants

Twenty-one recreational runners (12 females, 9 males; age: mean ± SD = 28.1 ± 8.3 years; weight: mean ± SD = 67.0 ± 12.2 kg; height: mean ± SD = 172.9 ± 9.7 cm; body mass index: mean ± SD = 22.3 ± 2.1 kg/m^2) were tested twice with a one week interval. Inclusion criteria for the study were (i) recreational runners: runners that run for enjoyment,[20] with a running volume of at least 10 km per week, and (ii) aged 18-45 years. Exclusion criteria were (i) individuals with a current running-related injury or a running-related injury over the past 6 months, which was defined as any running-related (training or competition) musculoskeletal pain in the lower limbs that causes a restriction on or stoppage of running (distance, speed, duration, or training) for at least 7 days or 3 consecutive scheduled training sessions, or that requires the runner to consult a physician or other health professional;[47] (ii) individuals with an injury resulting from activities other than running; (iii) novice runners: runners without any running experience or runners that did not perform their sport on a regular basis in the last year;[21, 28, 29] (iv) sprinters: runners who participate in running distances of 400 meters or less;[21] (v) ultra-marathon runners; (vi) elite athletes; (vii) runners who compete in other sports than running >6h/week; (viii) individuals with a history of major trauma and/or major orthopaedic surgery of the lumbopelvic region or lower extremity; and (ix) the presence of the following conditions or constitutions: neurological or vestibular impairments, pregnancy. Appropriate ethical approval was granted by the local ethical committee prior to the commencement of the study. Before participating in the study, all participants read and signed the informed consent form.

Procedures

All participants wore tight-fitting running pants, their own running shoes (which were identical for both test sessions), and a sports bra for the female participants. Male participants were asked to undress their upper body. Reflective markers (diameter 14 mm) were placed on the manubrium sterni and bilateral on the anterior superior iliac spine (ASIS), greater trochanter, lateral femoral epicondyle, fibular head and lateral malleolus. The same investigator placed all markers on all participants at both test sessions. All participants were instructed to run on a motorised treadmill (h/p/cosmos pulsar®, h/p/cosmos® sports & medical gmbh, Nusseldorf-Traunstein, Germany) at their preferred running speed (mean ± SD = 10.2 ± 1.2 km/h). A treadmill acclimatisation period of 6 minutes was used before running kinematics were measured.[22] After this acclimatisation period, digital videos were captured during 30 seconds with 2 tablets (iPad Air ®) sampling at 120 frames per second. Then, the treadmill was stopped and the participant turned 180°. The running direction of the treadmill was reversed at the same speed. As such, the camera position could remain unchanged to capture sagittal plane videos of the other leg after a new acclimatisation period of 2 minutes.

The frontal plane iPad was placed on a portable tripod perpendicular to the frontal plane at a height of 1.05 m and a distance of 2.0 m from the treadmill (Figure 1). The sagittal plane iPad was also placed on a portable tripod, perpendicular to the sagittal plane at a height of 0.80 m and a distance of 1.40 m from the treadmill (Figure 1). These positions were chosen to optimize visualization of the body regions of interest, and to minimize parallax error with our two-dimensional video analysis.

The video recordings were analyzed using a freely available software package (Kinovea® version 0.8.15, available at http://www.kinovea.org) by two raters (TJ, AB). Both raters were first trained by the principal investigator (BD). The test and retest videos were analyzed with at least one week interval. The first 10 participants were analyzed by rater 1, and the remaining 11 participants were analyzed by rater 2. The test and retest of a participant were always analyzed by the same rater. Previous studies have shown excellent intra- and intertester reliability of measuring angles with two-dimensional video analysis during running.[13, 23] Ten consecutive steps of both the right and left leg were analyzed.

In the frontal plane, the deepest landing position (near midstance) was determined visually by slowly advancing the video frame by frame.[13, 23] We defined this deepest landing position as the time point where there was maximal foot contact and no downward or upward movement occurred at the hip, knee and ankle.[13, 23] The intra- and interrater reliability of the detection of midstance in the frontal plane with two-dimensional video analysis has been shown to be excellent.[34] We defined 3 different angles in the frontal plane. The lateral trunk position angle was the angle between the vertical line starting at the ASIS of the stance leg, and a second line connecting the ASIS of the stance leg and the manubrium sterni (Figure 2A).[12] The smaller this angle, the more the trunk is positioned in the direction of the stance leg. The contralateral pelvic drop angle was the angle between the horizontal line starting at the ASIS of the stance leg and a second line connecting the ASIS of the stance and swing leg (Figure 2A).[13] The greater this angle, the greater the contralateral pelvic drop. The femoral adduction angle was the angle between the horizontal line starting at the ASIS of the stance leg and a second line connecting the ASIS of the stance leg with the midpoint of the tibiofemoral joint (knee joint centre) (Figure 2A).[13] Smaller femoral adduction angles represent greater femoral adduction. The hip adduction angle was calculated as the difference between the femoral adduction angle and the contralateral pelvic drop angle.[13] Smaller hip adduction angles represent greater hip adduction. All frontal plane angles were drawn at the same digital picture, at the same time frame (midstance) (Figure 2A). The frontal plane angles were chosen based on a combination of previous studies focusing on intra-tester and inter-tester reliability of two-dimensional measured angles,[13, 23] the relationship between two-dimensional and three-dimensional measured angles,[13, 23] and the evidence linking trunk, hip and pelvis frontal plane mechanics to running-related injuries.[1, 5, 9, 25, 27, 30, 31, 35]

In the sagittal plane, we defined two angles at initial contact and two angles at midstance. The intra- and interrater reliability of the detection of these gait events in the sagittal plane with a digital video camera capturing at 120 frames per second has been shown to be excellent when the same videos were rated on different days.[34] Initial contact was determined visually by slowly advancing the video frame by frame, and was defined as the first time that the foot touched the ground.[34] The foot inclination angle was defined as the angle between the horizontal and the sole of the foot (Figure 2B).[3, 34, 41, 43] Greater foot inclination angles represent greater foot inclination. The foot inclination angle was negative when a forefoot strike was used. The tibia inclination angle was defined as the angle between a vertical line starting at the lateral malleolus and a second line connecting the lateral malleolus and the fibular head (Figure 2B).[34, 41] Greater tibia inclination angles represent greater tibia inclination. The foot and tibia inclination angles were drawn on the same digital picture at initial contact (Figure 2B).

Midstance in the sagittal plane was defined visually in the same way as in the frontal plane, and was typically the point where the swing leg crossed the stance leg.[34] The ankle dorsiflexion angle was defined as the angle between the vertical line starting at the lateral malleolus and a second line connecting the lateral malleolus and the fibular head (Figure 2C). Greater ankle dorsiflexion angles represent greater ankle dorsiflexion. The knee flexion angle was defined as the angle between the line formed by the greater trochanter and the lateral femoral epicondyle, and a second line connecting the lateral femoral epicondyle and the lateral malleolus (Figure 2C).[8, 11] Smaller knee flexion angles represent greater knee flexion. The ankle dorsiflexion and knee flexion angles were drawn on the same digital picture (Figure 2C). Wille et al[43] showed that a subset of different easily measurable sagittal plane kinematic outcomes, including foot inclination and peak knee flexion, can be used to estimate important kinetic outcomes during running such as peak knee extensor moment, mechanical energy absorbed about the knee during loading response, peak patellofemoral joint reaction force, average vertical loading rate, peak vertical ground reaction force and braking impulse. Tibia inclination is typically related to “overstride” mechanics, which is described as a running pattern in which the foot lands further in front of the person’s center of mass.[41] An increased horizontal distance between the heel at initial contact and the center of mass has been related to peak knee extensor moment and braking impulse during running.[43] In addition, knee flexion, tibia inclination and ankle dorsiflexion have been related to running economy.[26]

Statistical analysis

Sequential estimation method

The sequential estimation method is a technique used to calculate the number of consecutive trials (steps) needed to obtain a stable mean for a certain variable, participant and movement.[18, 37] A sequential estimation was performed for each participant's block of 10 steps for each outcome variable (angle). We only used the data of both legs of the initial test. The cumulative mean was calculated by adding one trial at a time. The first data point was simply the angle of the first step. The second data point was the mean of the first 2 steps, the third data point was the mean of the first 3 steps and so on. The last calculation was simply the mean of all 10 data points. The criterion to obtain a stable mean for each angle within each block of 10 steps was met when the cumulative mean fell within the bandwidth of the 10-step mean ± 0.25 of the 10-step standard deviation and stayed there for the remaining steps (Figure 3).[18] This procedure was performed for each block of 10 values of each angle of each individual. The mean and standard deviation of this outcome (the number of steps needed to reach and maintain a stable mean) was calculated for each angle (Table 1).

Test-retest reliability

Based on the results of the sequential estimation method, the mean of 7 consecutive steps was calculated for each angle. The absolute differences between test and retest, and intraclass correlation coefficients ($ICC_{2,2}$) were calculated. The ICC values were interpreted as poor (<0.50), moderate (0.50-0.74), good (0.75-0.89) or excellent (0.90-1.00).[36] The standard error of measurement (SEM) and smallest detectable difference (SDD) were calculated using the formulas SD*√(1-ICC) and 1.96*SEM*√2 respectively.[42] The range of each angle within this study population was also calculated as reliability will improve as the total variance increase.[36]

All data were normally distributed, except for foot inclination (Shapiro-Wilk). Differences between angles at test and retest were compared with paired *t* tests. Foot inclination was compared with the Wilcoxon rank means test. Statistical significance was set at $P < .05$. All statistical analyses were performed using SPSS (SPSS Science, version 24 for Windows, USA).

RESULTS

Sequential estimation method

The minimal number of steps needed to reach and maintain a stable mean ranged between 5.8 and 7.0 (Table 1). Across all angles of both legs, mean ± SD = 6.3 ± 0.3 steps.

Test-retest reliability

Based on the mean of 7 steps, lateral trunk position, femoral adduction and foot inclination showed excellent reliability (ICC 0.90-0.99; SDD 1.3°-2.3°). Tibia inclination and ankle dorsiflexion showed good to excellent reliability (ICC 0.73-0.92; SDD 2.2°-4.8°). Hip adduction and knee flexion showed good reliability (ICC 0.82-0.89; SDD 2.3°-3.8°). Contralateral pelvic drop showed moderate to good reliability (ICC 0.59-0.77; SDD 2.7°-2.8°). The absolute differences, ICC, SEM and SDD values of all angles are presented in Table 2. All angles were not significantly different between test and retest ($P > .05$), except for lateral trunk position for the left leg ($P = .004$) (Table 3).

DISCUSSION

The purpose of this study was to determine the minimum number of steps required to obtain a stable mean to assess two-dimensional measured running kinematics and to examine the test-retest reliability of these two-dimensional measured kinematics. The most important findings are that two-dimensional video analysis can be used confidently in clinical settings on different days, and that the mean of at least 7 steps should be evaluated to reach and maintain a stable mean of a two-dimensional measured angle.

Even in a highly repetitive activity such as running, a certain amount of variability can be expected between consecutive steps. However, the number of steps needed to reliably assess an individual runner was previously unknown. Other studies using two-dimensional video analysis during running made arbitrary decisions to include four[13] or five[8, 23] steps. In the current study, we calculated the number of steps needed to achieve a stable mean for each outcome with the sequential estimation method. For most of the two-dimensional measured kinematic outcomes, the minimum number of steps was 6.3. This implies that future studies using the same two-dimensional video analysis methodology should include at least 7 steps to analyze the angles in the frontal and sagittal plane.

The evaluation of between-day reliability is essential to provide an indication of the magnitude of change needed in longitudinal studies to be considered meaningful. Without these analyses, it is impossible to ascertain whether a change measured with two-dimensional video analysis can be attributed to an intervention or to measurement error. Between-day variability in kinematic measurements can be driven by a number of factors, which can be categorized as intrinsic or extrinsic to the individual.[7] The intrinsic variability can be attributed to the variability that naturally occurs as a result of movement variability. Extrinsic sources of test-retest variability in the current study were mainly related to the methodology being used, including marker placement, gait event detection and the drawing of the angles. Despite these potential sources of variability, the good to excellent ICCs suggest that two-dimensional video analysis, based on the mean of 7 steps, can be used reliably to test and retest running kinematics in the frontal and sagittal plane.

We did observe some differences in reliability between certain angles. For example, the ICC of contralateral pelvic drop was lower compared to the other frontal and sagittal plane angles. However, it is important to note that despite this, contralateral pelvic drop produced similar absolute test-retest differences (1.3°-1.4°) compared to other angles (0.8°-2.8°). By definition, statistical variance in the test scores is the basis for reliability estimates.[36] Therefore, reliability will improve as the total variance increase, as the error component will account for a smaller proportion of it.[36] The smaller ICCs for contralateral pelvic drop may therefore also be attributed to the smaller range of this kinematic outcome.

Considering ICCs provide only a relative estimate of reliability, and limited indication of the precision of the measurement,[10, 42] we also calculated SEM and SDD to provide absolute measures of reliability, expressed in the same unit (degrees) as the original measure. The determination of these outcomes allows clinicians to define whether changes in kinematic outcomes at retest can be considered as real alterations in running kinematics, or measurement error. For example, lateral trunk position was significantly different between test and retest for the left leg, but the mean absolute difference between measures (1.0°) was smaller than the SDD (1.8°). Therefore, one can conclude that this statistical significant difference is not clinically meaningful with the current methodology.

Overall, our results show that the SDDs ranged between 1.3°-4.8° (Table 2). The clinical value of these numbers should be interpreted within the total range of each angle and the clinical reasoning processes of a clinician. For example, the SDD of contralateral pelvic drop was 2.7°-2.8°, but the total range across all participants was only 6.1° for the right leg and 9.6° for the left leg. This SDD corresponds to 44.0% and 29.2% of the range of respectively the right and left leg. In contrast, the SDD of foot inclination corresponds to only 6.5% and 7.9% of the range of respectively the right and left leg. As a consequence, differences between test and retest are probably easier to identify in angles where the SDD is a smaller proportion of the total range with the current two-dimensional video analysis methodology.

This is the first study to our knowledge to evaluate the test-retest reliability of two-dimensional video running analysis in the frontal and sagittal plane across different days, limiting our ability to compare findings to previous literature. Despite the widespread use of three-dimensional motion analysis in gait laboratories, only a relative small amount of studies have evaluated test-retest reliability of three-dimensional measured running kinematics.[2, 16, 32, 38] The diversity in study participants, methods, biomechanical modelling techniques, outcomes, statistical analyses and results impedes a general consistent conclusion of these studies.[24] Noehren et al[32] studied the between-session reliability of three-dimensional measured peak angles, extracted from a series of 10 individual curves (landing phases) in a group of 4 male and 6 female participants during treadmill running at approximately 12 km/h. These authors reported SEMs of 0.9° for hip adduction, 1.9° for knee flexion and 0.9° for ankle dorsiflexion, which corresponds to SDDs of respectively 2.5°, 5.3° and 2.5°. Interestingly, the results of our two-dimensional video analysis methodology are very similar to test-retest reliability outcomes reported with these three-dimensional motion analyses systems.

Given the validity of two-dimensional video analysis compared to three-dimensional video analysis,[13, 23] the results of the previously published intervention studies[14, 33, 39, 40, 44-46] and the relative small SDDs reported in this study, the current methodology offers possibilities to identify differences in running kinematics after interventions in future studies and clinical practice. Previously published intervention studies focusing on running retraining and/or strengthening have mainly used three-dimensional motion analysis systems to evaluate alterations in running kinematics.[14, 33, 39, 40, 44-46] To the best of our knowledge, only two previously published intervention studies used two-dimensional video analysis. Breen et al[6] performed a 6-week individualized running retraining intervention in a case series of 10 patients with exercise related running pain in the anterior compartment of the lower leg. Coaching cues were used to increase hip flexion during swing, increase cadence, maintain an upright torso and to achieve a midfoot strike pattern. By using two-dimensional video analysis in the sagittal plane, statistical significant changes were found in the kinematic outcomes of interest (foot inclination and tibia inclination at initial contact, maximum hip flexion during the swing phase and ankle dorsiflexion during midstance). Ferber et al[15] could not find a statistical significant difference in knee valgus after a 3-week hip abductor strengthening program in runners with patellofemoral pain. Considering the good to excellent reliability of two-dimensional video analysis of kinematics found in this study, these inconsistencies are likely the result of differing interventions rather than the measurement properties of testing methods. Importantly, the findings of the current study can be used as a solid scientific base to interpret the results of future intervention studies.

Some important clinical implications can be formulated based on the results of this study. The mean of at least 7 steps should be used to reach and maintain a stable mean. Although the current approach is more time-consuming than visual categorical rating of two-dimensional video recordings,[34] the good to excellent test-retest reliability outcomes allow clinicians to make better informed interpretations of kinematic changes after an intervention in clinical practice. Nevertheless, we want to emphasize that the clinical reasoning skills of a clinician within a multifactorial approach remain essential when aiming to address running kinematics of an individual.[4, 5]

A few limitations of the current study need to be considered. We only included non-injured participants in the study, limiting the generalizability of findings to clinical populations. Although the extrinsic sources of test-retest variability remain the same, the intrinsic running repeatability might be different in pathological populations.[19] However, based on the inclusion of both males and females in this study, we believe that the diversity within the study population was large enough to confidentially generalize the test-retest reliability results to a broad range of movement patterns. The two-dimensional videos were captured with high-speed videos (120 frames per second) and analyzed using a freely available specific software program (Kinovea). It is unclear whether cameras with lower sampling frequencies, or assessment using other software programs will produce similar reliability. Based on the finding to include 7 steps when analyzing two-dimensional angles, the current method with manual drawing of the angles can still take some time to perform. Another inherent limitation of two-dimensional video analysis is that movement patterns are reduced to two dimensions. Three-dimensional motion analysis remains the gold standard to perform a detailed running analysis. However, based on the results of this study and other studies, two-dimensional video analysis can be used as a reliable and valid alternative to assess running kinematics when three-dimensional motion analysis is not available.

CONCLUSION

This is the first study to report test-retest reliability of running kinematics with two-dimensional video analysis in the frontal and sagittal plane. First, we found that at least

7 steps should be included to reach and maintain a stable mean of a two-dimensional measured angle during running analysis. Second, good to excellent test-retest reliability was found, but the outcomes can differ between angles being measured. These findings further support the implementation of two-dimensional video analysis to assess running kinematics confidently in clinical settings.

CONFLICT OF INTEREST STATEMENT

None declared.

ETHICAL APPROVAL

The work has been approved by the appropriate ethical committees related to the institution in which it was performed (S60108 BE322201731705). Participants gave informed consent to the work.

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