

Relationship between 3D and 2D sagittal plane running kinematics during initial contact

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Published online: November 30, 2023

(Accepted for publication : November 15, 2023)

DOI:10.7752/jpes.2023.11350

Abstract

Approach: Both 2D and 3D biomechanical analyses (BA) offer valuable insights into running technique. While BA3D is considered the gold standard, it requires substantial investments, whereas BA2D is cost-effective and increasingly employed in clinical settings. The primary aim of this study was to establish correlations between sagittal plane angles derived from BA2D and BA3D for the pelvis, hip, knee, and ankle during the initial contact phase of running. **Methods:** Twelve runners, consisting of six females (34.0 ± 5.0 years, 53.0 ± 9.5 kg, and 162.0 ± 6.0 cm) and six males (32.0 ± 3.0 years, 70.0 ± 6.2 kg, and 175.0 ± 8.0 cm), underwent initial contact kinematics assessment using BA3D (Vicon Nexus 1.8 and Polygon 4 plug-in gait model) and BA2D (Kinovea, Version 0.9.3). Correlations between measurements were determined through linear regression (R^2), mean differences, Bland & Altman analysis (B&A), Pearson correlation coefficient (r) between BA2D and BA3D, and intraclass correlation coefficient (ICC). **Results:** The following results were obtained: Pelvis $R^2 = 0.67$, B&A = $7.32^\circ \pm 3.69^\circ$, $r = 0.818$ (sufficient, $p < 0.001$); Hip: $R^2 = 0.48$, B&A = $18.39^\circ \pm 5.56^\circ$, $r = 0.690$ (moderate, $p = 0.123$); Knee: $R^2 = 0.13$, B&A = $2.54^\circ \pm 5.38^\circ$, $r = 0.364$ (insufficient, $p < 0.001$); Ankle $R^2 = 0.15$, B&A = $-4.89^\circ \pm 4.22^\circ$, $r = 0.386$ (insufficient, $p < 0.001$). ICC for pelvis = 0.470; hip = 0.286; knee = 0.322; ankle = 0.213 (all statistically considered poor). **Conclusion:** The setup used during data collection can be easily reproduced by other professionals in a clinical setting. A low difference between BA2D and BA3D methods was observed based on B&A analysis. A linear relationship with moderate variability was established according to the Pearson correlation coefficient and coefficient of determination. However, poor agreement between BA3D and BA2D was found, as indicated by ICC. Therefore, caution is warranted when interpreting BA2D results relative to BA3D. The present study does not recommend other researchers to compare their BA2D with BA3D results conducted by different software than those used in our methods, this type of data must be considered individually across studies.

Key Words: kinematics, biomechanics, running, motion capture, lower limb.

Introduction

The surge in the number of runners has led to an increase in the incidence of athlete injuries (Schubert, Kempf & Heiderscheit, 2014; Rojo et al., 2017), consequently fostering a growing interest in comprehending the mechanisms of injury (Corrêa, 2014). Biomechanical analysis (BA) of motion through video (kinematics), initiated in the 19th century, is now readily accessible in clinical environments in two dimensions (BA2D) using conventional cameras (Dingenen et al., 2018a) or in three dimensions (BA3D) employing infrared cameras, which are more commonly found in specialized laboratories (Maus et al., 2015) interested in evaluating human movement and motor control in diverse conditions (Ferreira et al., 2023).

The study of kinematics is a focal point in many sports researches (Jamkrajang et al., 2022), and its significance has been demonstrated across diverse sports and activities like track and field (Saračević, Z., et al. 2018) and cycling (Liparoti et al., 2020). Additionally, other authors advocate for the application of kinematic data acquisition techniques to improve movement technique, enhance performance, and offer valuable training recommendations (Rucco et al., 2020a; Rucco et al., 2020b).

While BA3D is considered the gold standard for evaluating lower limb kinematics, BA2D remains prevalent due to its accessibility (De Oliveira et al., 2019). BA3D requires substantial investments, whereas BA2D can be conducted in a small space using affordable equipment such as a treadmill, a video camera, a tripod, and reflective markers, thus gaining popularity in clinical practice (Souza, 2016; Dingenen et al., 2018a; Maus et al., 2015). Additionally, with the current digital resources, results of BA3D are obtained rapidly and affordably, facilitating feedback to the athlete.

Despite being distinct methods, studies have reported associations between BA3D and BA2D (Dingenen et al., 2018b; Maykut et al., 2015; Metzler, Arampatzis & Brüggemann, 2002; Peebles et al., 2021; De Oliveira et al., 2019). There are various environments and methods for BA3D, such as Visual3D software -

C-Motion, Inc., Germantown, MD (Maykut et al., 2015); Qualisys Track Management software - Qualisys, Goteborg, Sweden (Peebles et al., 2021); and the Peak Motus system using Ariel Performance Analysis System software (Do Espírito Santo et al., 2017). Likewise, there are various environments for BA2D, such as Dartfish Motion Analysis Software - Dartfish, Fribourg, Switzerland (Maykut et al., 2015); custom interfaces in MATLAB - MathWorks Inc., Nantucket, MA (Peebles et al., 2021); Kinovea and SAPO (De Araújo & Duarte, 2022). The association between different data acquisition systems must be carefully considered, as kinematic data from BA2D and BA3D are sensitive to various intervening factors (BAZETT-JONES, 2023), including fatigue (Zandbergen et al., 2022), experience (Milner et al., 2022), and sex (Foch et al., 2023). Another intervening variable influencing running kinematics is the runner's range of motion, especially during the crucial initial contact phase of the run (Spadari; Brodt, 2021).

Properly interpreting sagittal plane running kinematics allows for the identification of footstrike patterns (Almeida, Davis & Lopes, 2015), energy optimization strategies (Anderson et al., 2020), and injury risk during initial contact (IC) (Xu et al., 2021). Therefore, reliably assessing running kinematics is essential for coaches to monitor technique, and clinicians to evaluate injury processes, all with the common aim of promoting athlete well-being. Thus, this study aims to evaluate the correlation of joint angles of the pelvis, hip, knee, and ankle during treadmill running between BA3D and BA2D techniques at the IC in experienced runners, in the sagittal plane.

Materials & methods

1.1 Participants

For the sample size calculation, G*Power 3.1.9.2 software (FAUL et al., 2007) was employed. An effect size of 0.8, an alpha error probability of 0.05, and a statistical power of 0.8 were used as reference values for the T-test family of tests. Consequently, a sample size of 12 runners was determined, comprising six females (34.0±5.0 years, 53.0±9.5 kg, and 162.0±6.0 cm) and six males (32.0±3.0 years, 70.0±6.2 kg, and 175.0±8.0 cm). This study received approval from the Research Ethics Committee of the University of Caxias do Sul (CAAE 45512121.5.0000.5341) and adhered to all ethical protocols (CNS Resolution 466/2012). All participants provided written informed consent. Inclusion criteria required all volunteers to have been running outdoor for at least one year without interruptions exceeding one week due to pain, injuries, or discomfort and to have participated in at least one 5 km race in the past year. Additionally, participants were required to run a minimum of three times per week, covering a weekly distance of 20 km to 100 km. Exclusion criteria stipulated that athletes should not exhibit any pain or discomfort that would hinder running during the tests.

1.2 Data Acquisition

Prior to data acquisition, a warm-up protocol was conducted on a treadmill (Super ATL – Inbramed, Porto Alegre, BR) for 7 minutes at a comfortable pace, with gradual speed increments until reaching the athlete's usual competition speed. The competition speed was maintained for 5 minutes and determined based on the athlete's previous 5 km race time. The average speed of the athletes was 14.0 ± 3.0 km/h (approximate pace ranging from 5:27 min/km to 3:32 min/km). All participants wore their customary competition shoes and comfortable clothing. Simultaneous acquisition of three-dimensional and two-dimensional kinematic data was performed. Reflective markers were placed on the posterior-superior iliac spines, anterior-superior iliac spines, greater trochanter, lateral knee condyle, lateral thigh, lateral malleolus, midpoint of the calf, upper and lower portions of the heel, Achilles tendon origin, and the head of the second metatarsal (Maykut et al., 2015) for subsequent analysis using Kinovea and NEXUS software (PUIG-DIVI ET AL., 2019; Hong & Mong, 2018).

AB3D Running Data Acquisition: Reflective markers were applied to anatomical landmarks by the same researcher, following the recommendations of the pluginGait model (NÜESCH ET AL., 2017). A motion capture system equipped with 7 integrated infrared cameras (VICON MX systems, Oxford Metrics Group, UK) was used. Kinematic data were collected at a sampling rate of 100 Hz for five acceptable trials.

AB2D Running Data Acquisition: For two-dimensional capture, a smartphone camera (Xiaomi Redmi Note 8, manufactured in 2019, with a video camera resolution of 3840x2160 pixels) was set to 1080p at 60fps and positioned on a tripod at a height of 1.2 m. The device was consistently placed in the same marked location for all sagittal plane assessments on the treadmill.

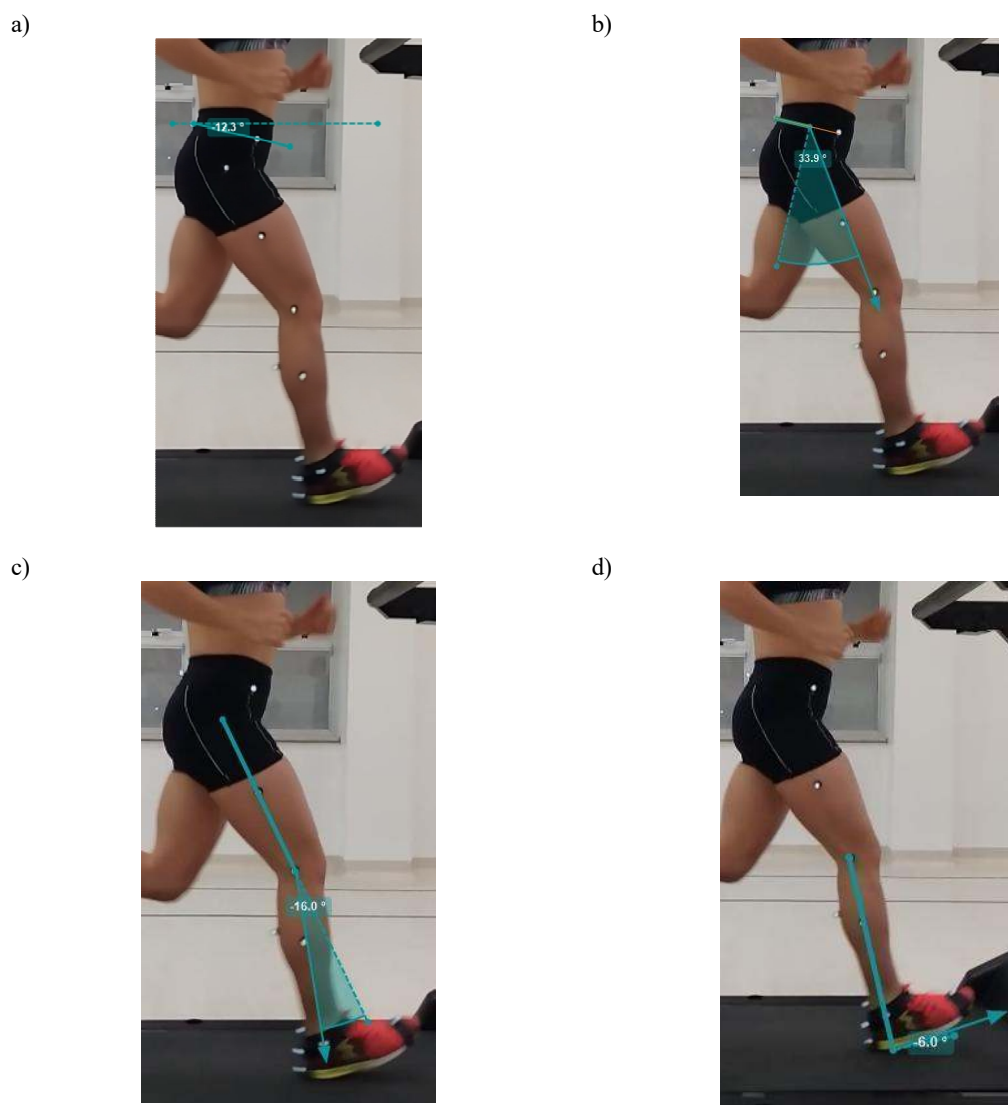
1.3 Data Analysis

BA3D Running Analysis: Kinematic outcome variables were collected using the NEXUS 1.8 system (Motion Capture Systems from Vicon OMG, Oxford, UK), following the recommendations of the pluginGait model (Nüesch et al., 2017; McClelland et al., 2010; Dixon, Böhm & Döderlein, 2012). Angles were recorded at IC (Initial Contact) - the first frame where contact between the treadmill and the individual's foot was identified. In the sagittal plane, pelvic angles (anterior and posterior tilt), hip angles (flexion and extension), knee angles (flexion and extension), and ankle angles (plantarflexion and dorsiflexion) were provided by the POLYGON 4 software (Motion Capture Systems from Vicon OMG, Oxford, UK).

BA2D Running Analysis: In BA2D analysis, the Kinovea program (Version 0.9.3 Charmant, 2020) was employed. Angles were measured at IC, defined as the first frame in which visible contact between the athlete's shoe sole and the treadmill was observed. The anterior and posterior pelvic tilt angle was determined as the angle formed between a line connecting the posterior-superior iliac spine to the anterior-superior iliac spine and the

horizontal line (Figure Ia). The hip flexion and extension angle was calculated as the angle formed between an imaginary line perpendicular to the line connecting the superior iliac spines and a line extending from the midpoint between the iliac spines to the lateral condyle of the knee (Figure Ib). The knee flexion and extension angle was formed by the extension of the line from the greater trochanter of the femur to the lateral condyle of the knee and the line from the lateral malleolus (Figure Ic). The plantarflexion and dorsiflexion angle was provided by the line connecting the lateral condyle of the knee through the lateral malleolus to the bottom edge of the shoe, with the line projected by the bottom edge of the shoe sole (Figure Id).

Figure I: Description of the angles evaluated in the two-dimensional kinematic biomechanical assessment



a) angle of the anterior and posterior version of the pelvis. b) angle of flexion and extension of the quadrilateral. c) knee extension and flexion angle. d) ankle plantarflexion and dorsiflexion angle

3.4 statistical analysis

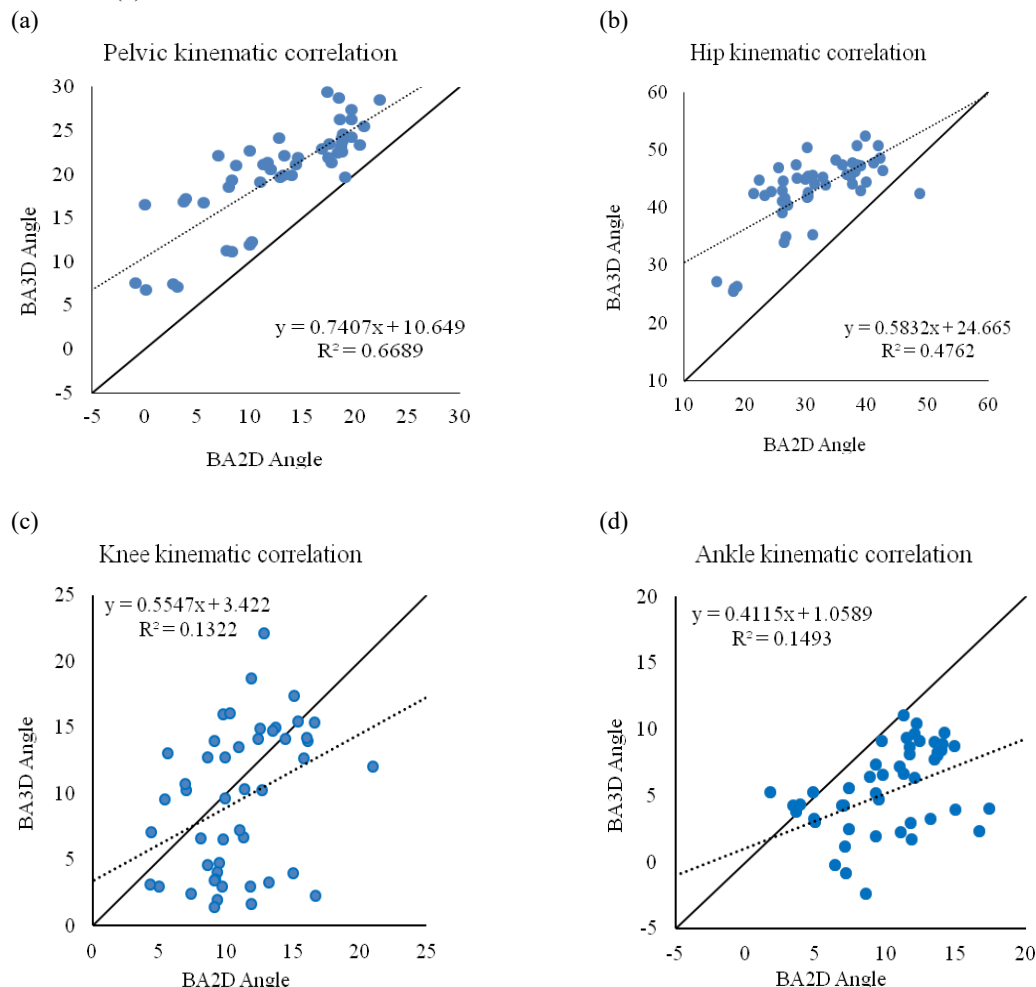
As dependent variables included ankle, knee, hip, and pelvic angles at the Initial Contact (IC), derived from both BA2D and BA3D, resulting in a total of eight dependent variables. Exploratory techniques of linear regression and Bland & Altman analysis (1986) were employed for the correlation between the sets of IC angle measurements from BA2D and BA3D, as recommended by Bland and Altman (1986), Hopkins (2009), and Liao & Capen (2011). Microsoft® Excel® for Microsoft 365 MSO (version 2304 Build 16.0.16327.20200, 32-bit) was used for this purpose, where a correlation plot was generated, and the goodness-of-fit measure of the proportion model of BA3D variation as a function of BA2D (R^2) was calculated, along with the first-degree equation representing it.

IBM SPSS Statistics software (version 23) was employed to calculate the Pearson correlation coefficient (r) between BA2D and BA3D, and for agreement assessment, the Intraclass Correlation Coefficient (ICC) at the 95% confidence level was calculated using a two-way mixed-effects model based on a single measurement with an absolute agreement definition. For the classification of Pearson's r , it was categorized as inadequate ($r < \pm 0.4$), moderate (r ranging from ± 0.4 to ± 0.7), and adequate ($r > \pm 0.7$) (Schober, Boer & Schwarte, 2018). Additionally, an independent T-test was conducted to compare the differences between BA2D and BA3D. The significance level adopted was $\alpha=0.05$.

Results

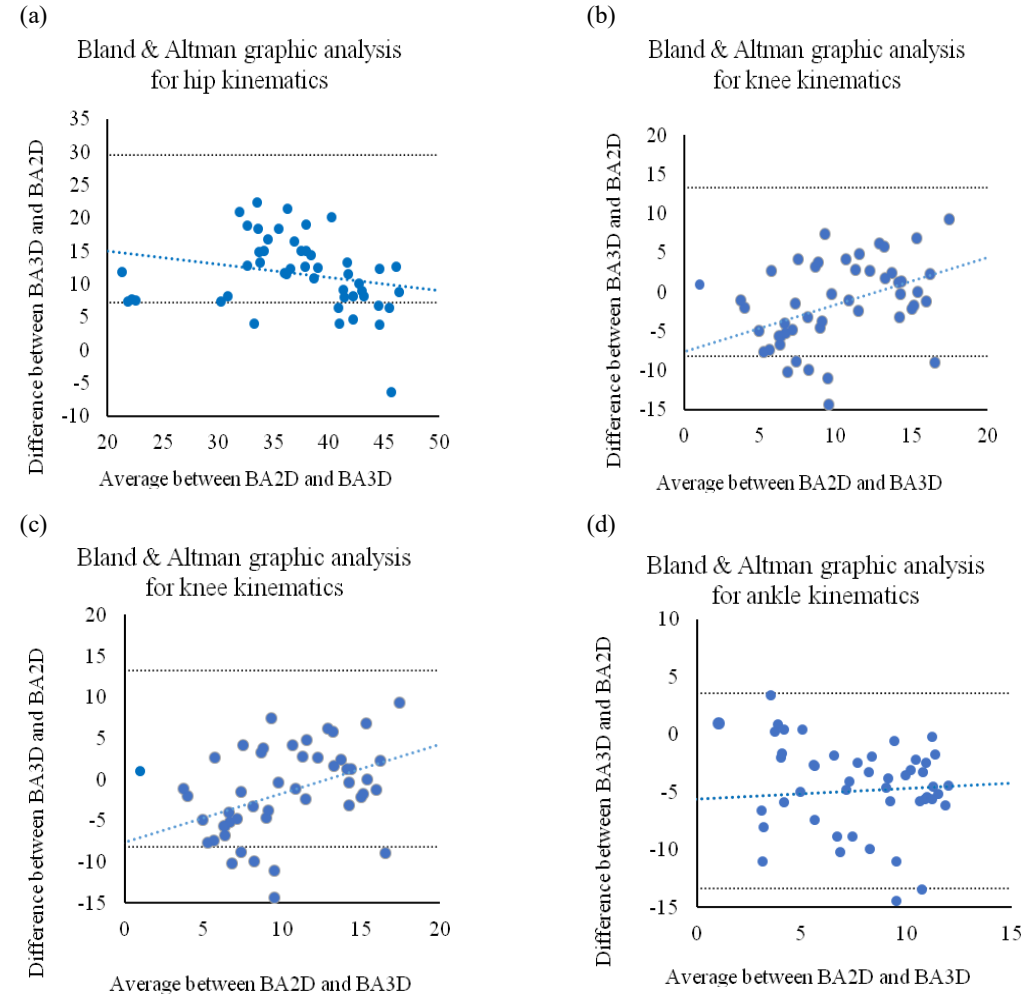
The correlation plots display the model fit measures indicating the proportion of BA3D variation as a function of BA2D with $R^2=0.67$ for the pelvis, $R^2=0.48$ for the hip, $R^2=0.13$ for the knee, and $R^2=0.15$ for the ankle (Figure II). Bland & Altman graphical analysis plots showed a mean difference between BA3D and BA2D of $7.32^\circ \pm 3.69^\circ$ for the pelvis, $18.39^\circ \pm 5.56^\circ$ for the hip, $2.54^\circ \pm 5.38^\circ$ for the knee, and $-4.89^\circ \pm 4.22^\circ$ for the ankle (Figure III). Pearson's correlation between BA3D and BA2D was statistically significant (<0.05) for all angles assessed, with $r=0.818$ (adequate) for the pelvis, $r=0.690$ (moderate) for the hip, $r=0.364$ (inadequate) for the knee, and $r=0.386$ (inadequate) for the ankle (Table 1). When comparing the assessed angles between BA3D and BA2D, only the knee angle measurement in BA3D was considered similar to BA2D ($p>0.05$); the other joints exhibited differences when comparing BA2D and BA3D ($p<0.05$). The ICC was statistically significant and poor for all evaluated segments (Table 1).

Figure II: Graphs of correlation results between angles from BA3D and BA2D of the pelvis (a), hip (b), knee (c) and ankle (d).



BA3D: Three-dimensional biomechanical analysis. BA2D: Two-dimensional Biomechanical Analysis. R^2 : model fit measure that indicates the proportion of variation in BA3D as a function of BA2D. The solid black line represents the perfect correlation between BA2D and BA3D. The dotted line represents the R^2 correction extrapolated to the limits of the graph. In the equation, Y represents the BA3D axis and x the BA2D axis.

Figure III: Graphs of Bland & Altman graphical analysis results for the angles from BA3D and BA2D of the pelvis (a), hip (b), knee (c) and ankle (d).



BA3D: Three-dimensional biomechanical analysis. BA2D: Two-dimensional Biomechanical Analysis. The blue dotted line represents the correlation between the X and Y axes (Average between BA2D and BA3D and Difference between BA3D and BA2D respectively). The dashed lines represent the margin of two standard deviations of the mean difference between BA3D and BA2D.

Table 1: Correlation results between angles from BA3D and BA2D of the pelvis, hip, knee and ankle.

Correlation between BA2D and BA3D	AB2D	AB3D	T-Test		Pearson Correlation		Intraclass Correlation Coefficient	
	M ± DP	M ± DP	T	p _(t)	R	p _(r)	ICC 95% (47,47)	p _(CCI)
Pelvic	12,84 ± 6,33	20,16 ± 5,73	-5,937	<0,001*	0,818	< 0,001*	0,470	<0,001*
Hip	31,41 ± 7,51	42,98 ± 6,35	-8,154	<0,001*	0,690	< 0,001*	0,286	<0,001*
Knee	11,01 ± 3,61	9,53 ± 5,51	1,556	0,131	0,364	0,123	0,322	0,010*
Ankle	10,10 ± 3,69	5,21 ± 3,93	6,279	<0,001*	0,386	< 0,001*	0,213	0,003*

M: Average. SD: Standard deviation. BA3D: Three-dimensional biomechanical analysis. BA2D: Two-dimensional Biomechanical Analysis. p_(t) : significance index p for the T test for independent measurements. p_(r) : significance index p for the Pearson correlation. *: Highlights significant p (<0.05)

Discussion

Numerous studies utilize kinematic analysis to identify movement patterns and deviations with the aim of assisting coaches and runners in managing discomfort, reducing the risk of injuries, and enhancing performance (Schache et al., 2011; Yong et al., 2020). These analyses are conducted in both three dimensions (Sinclair, 2016) and two dimensions (Bramah et al., 2018), two techniques with different accessibility and methods. Therefore, the primary objective of this study was to assess the correlation of angular results from 2D and 3D kinematic analysis at the main lower limb joints in the sagittal plane during the Initial Contact (IC) phase of running. The results demonstrated a small mean difference between the outcomes of 2D and 3D kinematic analysis, which was lower than the minimal detectable clinical difference for knees ($<6.9^\circ$) and ankles ($<6.9^\circ$), but slightly higher for the pelvis ($>4.0^\circ$) and hip ($>3.7^\circ$) (Bramah et al., 2021).

Despite the low differences between the methods, the knee and ankle angles did not show satisfactory correlation. One justification for the absence of correlation between knee angles in 2D and 3D kinematic analysis is that 2D analysis neglects movements in the transverse and frontal planes, and these distal joints depend on measurements of proximal joints, leading to an accumulation of measurement errors. In contrast, 3D kinematic analysis calculates movement planes individually for each segment, which circumvents the perspective problem presented by 2D analysis.

Other studies have also conducted correlation analysis between 2D and 3D kinematic analysis. Mousavi et al. (2020) evaluated kinematics in the sagittal and frontal planes of 25 female runners, using a smartphone for 2D capture and a video camera system for 3D capture, demonstrating validity between the two techniques through ICC, minimal detectable difference, and standard error of measurement techniques. Dingenen et al. (2018b) also used the frontal plane to assess 15 elite runners, observing pelvic drop, hip adduction/abduction, and knee adduction/abduction, demonstrating high validity. The authors recommended implementing 2D video analysis as an alternative methodology for frontal plane motion analysis based on the results of ICC, minimal detectable difference, and standard error of measurement. Similarly, Maycut et al. (2015) used the frontal plane to assess 24 male and female collegiate cross-country runners and concluded that 2D kinematic analysis could be used as a substitute for 3D analysis. However, they only used Pearson's correlation for this assessment and did not present ICC results between 2D and 3D analysis. Esculier et al. (2018) evaluated foot strike patterns between 2D and 3D kinematic analysis in 60 runners with patellofemoral pain, using ICC and finding satisfactory validity between the techniques, although they did not utilize ICC technique.

However, in the aforementioned studies by Esculier et al. (2018), Maycut et al. (2015), Dingenen et al. (2018b), and Mousavi (2020), the authors did not specify the technique used for calculating ICC. Different ICC estimation methods can lead to significant differences in the final index result (Koo & Li, 2016). Additionally, only a few of the aforementioned studies employed all the assessment techniques evaluated in the present study, such as Pearson correlation (Field, 2009), Bland & Altman (Haghighyegh et al., 2020), and r^2 (Field, 2009). In addition to the highlighted studies, some reviews have assessed the validity of 2D kinematic analysis (BA2D). The systematic review by De Oliveira et al. (2019) demonstrated strong evidence that BA2D for evaluating footstrike patterns is reliable; however, similar to the present study, it has limited evidence of being valid. In agreement, Leporace et al. (2023) concluded that the BA2D method exhibits good to excellent reliability for measuring joint angles during running. Still, the validity of BA2D compared to BA3D varies from low to moderate for most evaluated parameters. Furthermore, due to the variation in methodologies adopted among studies, it is essential that procedures be standardized, and training should be an integral part of future research involving BA2D. It is also emphasized that BA2D should not be considered a simplified representation of 3D measurements.

It is important to note that the present study has some limitations. Firstly, these results are limited to healthy runners with no recent history of injuries or discomfort during running; therefore, caution should be exercised when generalizing to injured runners or other conditions. Moreover, the assessment conducted only evaluated the moment of initial contact during running, so our results cannot be extrapolated to the entire running cycle. Another limitation is related to the evaluation in only one plane, the sagittal plane. However, it is worth noting that the setup used during data collection can be easily reproduced by other professionals in a clinical setting. Nonetheless, it is important to emphasize that comparisons between studies should be made with each study's own assessment technique or software. In other words, the present study does not recommend other researchers to compare their BA2D with BA3D results conducted by different software than those used in our methods. Further research is suggested with a larger number of participants, different assessment protocols, evaluation of other phases of running, and assessment in the frontal and transverse planes.

Conclusions

The results of the present study led to the conclusion that the kinematics at initial contact exhibit a low difference between the BA2D and BA3D methods, as indicated by Bland & Altman analysis, assessed using BA2D with Kinovea software, and BA3D with a VICON motion capture system, for the pelvis, hip, and knee joints. A linear relationship with a moderate proportion of variability is observed, as evidenced by Pearson's correlation and the coefficient of determination (R^2). Due to the results being reliable when replicating the use of BA2D, caution should be taken when comparing it with BA3D, as each method and protocol has its own

variables that interfere in the evaluation. However, poor agreement between BA3D and BA2D is detected, as demonstrated by the ICC. In addition, other studies also agreed that there was a lack of statistical descriptions, which implies the analysis interpretation of the data found. Therefore, caution is advised when interpreting BA2D results in comparison to BA3D.

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