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Test-retest reliability of two-dimensional video analysis during running Peer-reviewed author version

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ABSTRACT 2 Objectives: To examine test-retest reliability of two-dimensional measured frontal and 3 sagittal plane kinematics during running, and to determine how many steps to include 4 to reach and maintain a stable mean. 5 6 Design: Reliability study 7 Setting: Research laboratory 8 Participants: Twenty-one recreational runners Main Outcome Measures: Lateral trunk position, contralateral pelvic drop, femoral 9 adduction, hip adduction, knee flexion and ankle dorsiflexion during midstance, and 10 foot and tibia inclination at initial contact were measured with two-dimensional video 11 analysis during running for 10 consecutive steps for both legs. All participants were 12 tested twice one week apart. A sequential estimation method was used to determine 13 the number of steps needed to reach a stable mean. Intraclass correlation coefficients 14 (ICC) and smallest detectable differences (SDD) were calculated. 15 Results: The minimal number of steps was 6.3±0.3. Lateral trunk position, femoral 16 adduction and foot inclination showed excellent reliability (ICC 0.90-0.99;SDD 1.3°-17 18 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 19 0.82-0.89;SDD 2.3°-3.8°). Contralateral pelvic drop showed moderate to good 20 reliability (ICC 0.59-0.77;SDD 2.7°-2.8°). 21 22 Conclusion: Two-dimensional video analysis is reliable to assess running kinematics

²³ on different days. The mean of at least 7 steps should be included.

<u>KEYWORDS</u>

Running, kinematics, two-dimensional video analysis, reliability

<u>HIGHLIGHTS</u>

- At least **7** steps should be used to reach and maintain a stable mean.
- 29 Good to excellent test-retest reliability was found for 2D video analysis.
- 30 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 33 running may be related to a broad range of outcomes such as running performance,¹⁷ 34 running economy²⁶ and running-related injuries.^{1, 5, 9, 25, 27, 30, 31, 35} In addition, the ability 35 to measure changes in lower extremity running kinematics is essential to further 36 understand the effect of interventions. The majority of published studies reporting 37 kinematics in runners,1, 25, 27, 30, 31, 35 have used three-dimensional motion analysis 38 systems, which are considered the gold standard for a detailed running analysis.²³ 39 However, this methodology requires expensive equipment, is time-consuming and is 40 currently not widely available in clinical settings where physical therapists or athletic 41 trainers work with runners. Reliable, accurate and inexpensive methods that are time-42 43 efficient and user-friendly are required to facilitate the evaluation of running kinematics in clinical settings. 44

Pipkin et al³⁴ 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 al¹³ 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-57 dimensional measured contralateral pelvic drop was also significantly related to the 58 three-dimensional measured contralateral pelvic drop kinematic profile across the 59 majority of the stance phase. In accordance with the study of Maykut et al²³, excellent 60 intra- and intertester reliability was found for all frontal plane angles, including 61 contralateral pelvic drop, femoral adduction and hip adduction, when the same videos 62 were evaluated on different days. In the sagittal plane, different kinematic outcomes 63 resulting from two-dimensional video analysis have been reported at initial contact and 64 midstance, such as foot inclination,^{3, 34, 41, 43} tibia inclination^{34, 41} and knee flexion.^{8, 41} 65 Damsted et al⁸ evaluated within and between day intra- and intertester reliability of two-66 dimensional video measures of knee and hip flexion angles at initial contact during 67 running. However, the magnitude of change beyond measurement error was not 68 calculated. Therefore, the test-retest reliability of two-dimensional frontal and sagittal 69 plane analysis when the runner is tested on different days remains unclear. This is 70 important because assessment and re-assessment of running kinematics in a clinical 71 setting often occur on different days. 72

The current limitation of unknown test-retest reliability when using two-dimensional 73 video analysis collected on different days, as opposed to the same video being rated 74 on different days, hampers the interpretation of changes in outcomes when retesting 75 an individual runner. Based on the inter-session variability of running kinematics and 76 the increasing scientific support for running retraining to treat lower limb injuries.⁵ this 77 information is essential to use two-dimensional video analysis effectively before and 78 after interventions. Furthermore, given the intrinsic variability of human running,¹⁹ it is 79 not clear how many steps should be included and averaged when assessing two-80 dimensional measured kinematic outcomes in order to obtain stable gait data. 81

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 testretest reliability of these two-dimensional measured kinematics.

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<u>METHODS</u>

90 Participants

Twenty-one recreational runners (12 females, 9 males; age: mean \pm SD = 28.1 \pm 8.3 91 years; weight: mean \pm SD = 67.0 \pm 12.2 kg; height: mean \pm SD = 172.9 \pm 9.7 cm; body 92 mass index: mean \pm SD = 22.3 \pm 2.1 kg/m²) were tested twice with a one week interval. 93 Inclusion criteria for the study were (i) recreational runners: runners that run for 94 enjoyment,²⁰ with a running volume of at least 10 km per week, and (ii) aged 18-45 95 years. Exclusion criteria were (i) individuals with a current running-related injury or a 96 running-related injury over the past 6 months, which was defined as any running-97 related (training or competition) musculoskeletal pain in the lower limbs that causes a 98 restriction on or stoppage of running (distance, speed, duration, or training) for at least 99 7 days or 3 consecutive scheduled training sessions, or that requires the runner to 100 101 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 102 experience or runners that did not perform their sport on a regular basis in the last 103 year;^{21, 28, 29} (iv) sprinters: runners who participate in running distances of 400 meters 104 or less;²¹ (v) ultra-marathon runners; (vi) elite athletes; (vii) runners who compete in 105 other sports than running >6h/week; (viii) individuals with a history of major trauma 106

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.

112 <u>Procedures</u>

All participants wore tight-fitting running pants, their own running shoes (which were 113 identical for both test sessions), and a sports bra for the female participants. Male 114 participants were asked to undress their upper body. Reflective markers (diameter 14 115 mm) were placed on the manubrium sterni and bilateral on the anterior superior iliac 116 spine (ASIS), greater trochanter, lateral femoral epicondyle, fibular head and lateral 117 malleolus. The same investigator placed all markers on all participants at both test 118 sessions. All participants were instructed to run on a motorised treadmill (h/p/cosmos 119 pulsar®, h/p/cosmos® sports & medical gmbh, Nusseldorf-Traunstein, Germany) at 120 their preferred running speed (mean ± SD = 10.2 ± 1.2 km/h). A treadmill 121 acclimatisation period of 6 minutes was used before running kinematics were 122 measured.²² After this acclimatisation period, digital videos were captured during 30 123 seconds with 2 tablets (iPad Air ®) sampling at 120 frames per second. Then, the 124 treadmill was stopped and the participant turned 180°. The running direction of the 125 treadmill was reversed at the same speed. As such, the camera position could remain 126 unchanged to capture sagittal plane videos of the other leg after a new acclimatisation 127 period of 2 minutes. 128

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 135 (Kinovea® version 0.8.15, available at http://www.kinovea.org) by two raters (TJ, AB). 136 Both raters were first trained by the principal investigator (BD). The test and retest 137 videos were analyzed with at least one week interval. The first 10 participants were 138 analyzed by rater 1, and the remaining 11 participants were analyzed by rater 2. The 139 test and retest of a participant were always analyzed by the same rater. Previous 140 studies have shown excellent intra- and intertester reliability of measuring angles with 141 two-dimensional video analysis during running.^{13, 23} Ten consecutive steps of both the 142 143 right and left leg were analyzed.

In the frontal plane, the deepest landing position (near midstance) was determined 144 visually by slowly advancing the video frame by frame.^{13, 23} We defined this deepest 145 landing position as the time point where there was maximal foot contact and no 146 downward or upward movement occurred at the hip, knee and ankle.^{13, 23} The intra-147 and interrater reliability of the detection of midstance in the frontal plane with two-148 dimensional video analysis has been shown to be excellent.³⁴ We defined 3 different 149 angles in the frontal plane. The lateral trunk position angle was the angle between the 150 vertical line starting at the ASIS of the stance leg, and a second line connecting the 151 ASIS of the stance leg and the manubrium sterni (Figure 2A).¹² The smaller this angle, 152 the more the trunk is positioned in the direction of the stance leg. The contralateral 153 pelvic drop angle was the angle between the horizontal line starting at the ASIS of the 154 stance leg and a second line connecting the ASIS of the stance and swing leg (Figure 155 2A).¹³ The greater this angle, the greater the contralateral pelvic drop. The femoral 156

adduction angle was the angle between the horizontal line starting at the ASIS of the 157 stance leg and a second line connecting the ASIS of the stance leg with the midpoint 158 of the tibiofemoral joint (knee joint centre) (Figure 2A).¹³ Smaller femoral adduction 159 angles represent greater femoral adduction. The hip adduction angle was calculated 160 as the difference between the femoral adduction angle and the contralateral pelvic drop 161 angle.¹³ Smaller hip adduction angles represent greater hip adduction. All frontal plane 162 angles were drawn at the same digital picture, at the same time frame (midstance) 163 (Figure 2A). The frontal plane angles were chosen based on a combination of previous 164 studies focusing on intra-tester and inter-tester reliability of two-dimensional measured 165 angles,^{13, 23} the relationship between two-dimensional and three-dimensional 166 measured angles,^{13, 23} and the evidence linking trunk, hip and pelvis frontal plane 167 mechanics to running-related iniuries.^{1, 5, 9, 25, 27, 30, 31, 35} 168

In the sagittal plane, we defined two angles at initial contact and two angles at 169 midstance. The intra- and interrater reliability of the detection of these gait events in 170 171 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 172 contact was determined visually by slowly advancing the video frame by frame, and 173 was defined as the first time that the foot touched the ground.³⁴ The foot inclination 174 angle was defined as the angle between the horizontal and the sole of the foot (Figure 175 2B).^{3, 34, 41, 43} Greater foot inclination angles represent greater foot inclination. The foot 176 inclination angle was negative when a forefoot strike was used. The tibia inclination 177 angle was defined as the angle between a vertical line starting at the lateral malleolus 178 and a second line connecting the lateral malleolus and the fibular head (Figure 2B).^{34,} 179 ⁴¹ Greater tibia inclination angles represent greater tibia inclination. The foot and tibia 180 inclination angles were drawn on the same digital picture at initial contact (Figure 2B). 181

Midstance in the sagittal plane was defined visually in the same way as in the frontal 182 plane, and was typically the point where the swing leg crossed the stance leg.³⁴ The 183 ankle dorsiflexion angle was defined as the angle between the vertical line starting at 184 the lateral malleolus and a second line connecting the lateral malleolus and the fibular 185 head (Figure 2C). Greater ankle dorsiflexion angles represent greater ankle 186 dorsiflexion. The knee flexion angle was defined as the angle between the line formed 187 by the greater trochanter and the lateral femoral epicondyle, and a second line 188 connecting the lateral femoral epicondyle and the lateral malleolus (Figure 2C).^{8, 11} 189 Smaller knee flexion angles represent greater knee flexion. The ankle dorsiflexion and 190 knee flexion angles were drawn on the same digital picture (Figure 2C). Wille et al⁴³ 191 showed that a subset of different easily measurable sagittal plane kinematic outcomes, 192 including foot inclination and peak knee flexion, can be used to estimate important 193 194 kinetic outcomes during running such as peak knee extensor moment, mechanical energy absorbed about the knee during loading response, peak patellofemoral joint 195 reaction force, average vertical loading rate, peak vertical ground reaction force and 196 braking impulse. Tibia inclination is typically related to "overstride" mechanics, which 197 is described as a running pattern in which the foot lands further in front of the person's 198 center of mass.⁴¹ An increased horizontal distance between the heel at initial contact 199 and the center of mass has been related to peak knee extensor moment and braking 200 impulse during running.43 In addition, knee flexion, tibia inclination and ankle 201 dorsiflexion have been related to running economy.²⁶ 202

203 <u>Statistical analysis</u>

204 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 207 participant's block of 10 steps for each outcome variable (angle). We only used the 208 data of both legs of the initial test. The cumulative mean was calculated by adding one 209 trial at a time. The first data point was simply the angle of the first step. The second 210 data point was the mean of the first 2 steps, the third data point was the mean of the 211 first 3 steps and so on. The last calculation was simply the mean of all 10 data points. 212 The criterion to obtain a stable mean for each angle within each block of 10 steps was 213 met when the cumulative mean fell within the bandwidth of the 10-step mean ± 0.25 of 214 the 10-step standard deviation and stayed there for the remaining steps (Figure 3).¹⁸ 215 216 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 217 needed to reach and maintain a stable mean) was calculated for each angle (Table 1). 218

219 Test-retest reliability

Based on the results of the sequential estimation method, the mean of $\frac{7}{7}$ consecutive 220 steps was calculated for each angle. The absolute differences between test and retest, 221 and intraclass correlation coefficients (ICC_{2,2}) were calculated. The ICC values were 222 interpreted as poor (<0.50), moderate (0.50-0.74), good (0.75-0.89) or excellent (0.90-223 1.00).³⁶ The standard error of measurement (SEM) and smallest detectable difference 224 (SDD) were calculated using the formulas SD* $\sqrt{(1-ICC)}$ and 1.96*SEM* $\sqrt{2}$ 225 respectively.⁴² The range of each angle within this study population was also calculated 226 as reliability will improve as the total variance increase.³⁶ 227

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).

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RESULTS

235 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 \pm SD = 6.3 \pm 0.3 steps.

239 <u>Test-retest reliability</u>

Based on the mean of 7 steps, lateral trunk position, femoral adduction and foot 240 inclination showed excellent reliability (ICC 0.90-0.99; SDD 1.3°-2.3°). Tibia inclination 241 and ankle dorsiflexion showed good to excellent reliability (ICC 0.73-0.92; SDD 2.2°-242 4.8°). Hip adduction and knee flexion showed good reliability (ICC 0.82-0.89; SDD 243 2.3°-3.8°). Contralateral pelvic drop showed moderate to good reliability (ICC 0.59-0.77; 244 SDD 2.7°-2.8°). The absolute differences, ICC, SEM and SDD values of all angles are 245 presented in Table 2. All angles were not significantly different between test and retest 246 (P > .05), except for lateral trunk position for the left leg (P = .004) (Table 3). 247

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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 257 be expected between consecutive steps. However, the number of steps needed to 258 reliably assess an individual runner was previously unknown. Other studies using two-259 dimensional video analysis during running made arbitrary decisions to include four¹³ or 260 five^{8, 23} steps. In the current study, we calculated the number of steps needed to 261 achieve a stable mean for each outcome with the sequential estimation method. For 262 most of the two-dimensional measured kinematic outcomes, the minimum number of 263 steps was 6.3. This implies that future studies using the same two-dimensional video 264 265 analysis methodology should include at least 7 steps to analyze the angles in the frontal and sagittal plane. 266

The evaluation of between-day reliability is essential to provide an indication of the 267 magnitude of change needed in longitudinal studies to be considered meaningful. 268 Without these analyses, it is impossible to ascertain whether a change measured with 269 two-dimensional video analysis can be attributed to an intervention or to measurement 270 error. Between-day variability in kinematic measurements can be driven by a number 271 of factors, which can be categorized as intrinsic or extrinsic to the individual.⁷ The 272 intrinsic variability can be attributed to the variability that naturally occurs as a result of 273 movement variability. Extrinsic sources of test-retest variability in the current study 274 were mainly related to the methodology being used, including marker placement, gait 275 event detection and the drawing of the angles. Despite these potential sources of 276 variability, the good to excellent ICCs suggest that two-dimensional video analysis, 277

based on the mean of 7 steps, can be used reliably to test and retest running
kinematics in the frontal and sagittal plane.

280 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 281 plane angles. However, it is important to note that despite this, contralateral pelvic drop 282 produced similar absolute test-retest differences (1.3°-1.4°) compared to other angles 283 (0.8°-2.8°). By definition, statistical variance in the test scores is the basis for reliability 284 estimates.³⁶ Therefore, reliability will improve as the total variance increase, as the 285 error component will account for a smaller proportion of it.³⁶ The smaller ICCs for 286 contralateral pelvic drop may therefore also be attributed to the smaller range of this 287 288 kinematic outcome.

Considering ICCs provide only a relative estimate of reliability, and limited indication of 289 the precision of the measurement,^{10, 42} we also calculated SEM and SDD to provide 290 absolute measures of reliability, expressed in the same unit (degrees) as the original 291 measure. The determination of these outcomes allows clinicians to define whether 292 changes in kinematic outcomes at retest can be considered as real alterations in 293 running kinematics, or measurement error. For example, lateral trunk position was 294 significantly different between test and retest for the left leg, but the mean absolute 295 difference between measures (1.0°) was smaller than the SDD (1.8°). Therefore, one 296 can conclude that this statistical significant difference is not clinically meaningful with 297 the current methodology. 298

Overall, our results show that the SDDs ranged between $1.3^{\circ}-4.8^{\circ}$ (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 $2.7^{\circ}-2.8^{\circ}$, but the total range across all participants was

303 only 6.1° for the right leg and 9.6° for the left leg. This SDD corresponds to 44.0% and 304 29.2% of the range of respectively the right and left leg. In contrast, the SDD of foot 305 inclination corresponds to only 6.5% and 7.9% of the range of respectively the right 306 and left leg. As a consequence, differences between test and retest are probably easier 307 to identify in angles where the SDD is a smaller proportion of the total range with the 308 current two-dimensional video analysis methodology.

This is the first study to our knowledge to evaluate the test-retest reliability of two-309 dimensional video running analysis in the frontal and sagittal plane across different 310 days, limiting our ability to compare findings to previous literature. Despite the 311 widespread use of three-dimensional motion analysis in gait laboratories, only a 312 relative small amount of studies have evaluated test-retest reliability of three-313 dimensional measured running kinematics.^{2, 16, 32, 38} The diversity in study participants, 314 methods, biomechanical modelling techniques, outcomes, statistical analyses and 315 results impedes a general consistent conclusion of these studies.²⁴ Noehren et al³² 316 studied the between-session reliability of three-dimensional measured peak angles, 317 extracted from a series of 10 individual curves (landing phases) in a group of 4 male 318 and 6 female participants during treadmill running at approximately 12 km/h. These 319 authors reported SEMs of 0.9° for hip adduction, 1.9° for knee flexion and 0.9° for ankle 320 dorsiflexion, which corresponds to SDDs of respectively 2.5°, 5.3° and 2.5°. 321 Interestingly, the results of our two-dimensional video analysis methodology are very 322 similar to test-retest reliability outcomes reported with these three-dimensional motion 323 analyses systems. 324

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,} and the relative small SDDs reported in this study, the current methodology

offers possibilities to identify differences in running kinematics after interventions in 328 future studies and clinical practice. Previously published intervention studies focusing 329 on running retraining and/or strengthening have mainly used three-dimensional motion 330 analysis systems to evaluate alterations in running kinematics.^{14, 33, 39, 40, 44-46} To the 331 best of our knowledge, only two previously published intervention studies used two-332 dimensional video analysis. Breen et al⁶ performed a 6-week individualized running 333 retraining intervention in a case series of 10 patients with exercise related running pain 334 in the anterior compartment of the lower leg. Coaching cues were used to increase hip 335 flexion during swing, increase cadence, maintain an upright torso and to achieve a 336 337 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 338 inclination and tibia inclination at initial contact, maximum hip flexion during the swing 339 phase and ankle dorsiflexion during midstance). Ferber et al¹⁵ could not find a 340 statistical significant difference in knee valgus after a 3-week hip abductor 341 strengthening program in runners with patellofemoral pain. Considering the good to 342 excellent reliability of two-dimensional video analysis of kinematics found in this study, 343 these inconsistencies are likely the result of differing interventions rather than the 344 measurement properties of testing methods. Importantly, the findings of the current 345 study can be used as a solid scientific base to interpret the results of future intervention 346 studies. 347

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-356 injured participants in the study, limiting the generalizability of findings to clinical 357 populations. Although the extrinsic sources of test-retest variability remain the same, 358 the intrinsic running repeatability might be different in pathological populations.¹⁹ 359 However, based on the inclusion of both males and females in this study, we believe 360 that the diversity within the study population was large enough to confidentially 361 generalize the test-retest reliability results to a broad range of movement patterns. The 362 363 two-dimensional videos were captured with high-speed videos (120 frames per 364 second) and analyzed using a freely available specific software program (Kinovea). It is unclear whether cameras with lower sampling frequencies, or assessment using 365 other software programs will produce similar reliability. Based on the finding to include 366 7 steps when analyzing two-dimensional angles, the current method with manual 367 drawing of the angles can still take some time to perform. Another inherent limitation 368 of two-dimensional video analysis is that movement patterns are reduced to two 369 dimensions. Three-dimensional motion analysis remains the gold standard to perform 370 a detailed running analysis. However, based on the results of this study and other 371 studies, two-dimensional video analysis can be used as a reliable and valid alternative 372 to assess running kinematics when three-dimensional motion analysis is not available. 373

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CONCLUSION

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

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

383	CONFLICT OF INTEREST STATEMENT
384	None declared.
385	
386	ETHICAL APPROVAL
387	The work has been approved by the appropriate ethical committees related to the
388	institution in which it was performed (S60108 BE322201731705). Participants gave
389	informed consent to the work.
390	
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392	This research did not receive any specific grant from funding agencies in the public,
393	commercial, or not-for-profit sectors.
394	

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