

KINEMATIC ANALYSIS OF BICYCLE PEDALLING USING 2D AND 3D MOTION CAPTURE SYSTEMS

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The main purpose was to test the validity and sensibility of two motion capture systems (sophisticated 3D vs low-cost 2D) to analyse angular kinematics during pedalling. Twelve trained cyclists participated, and were analysed in three different saddle heights at a random order: their preferred one, 2% lower and 2% higher. High correlations were found between 2D and 3D systems in all the measured variables. The 2D system was sensitive as the 3D to detect small changes in saddle height. In conclusion, the 2D motion capture system is valid and sensitive for angular kinematic analysis in the sagittal plane. It underestimated 2-3° hip and knee extensions, without differences in the ankle extension, while joint flexion were also underestimated 3-4°, 2° and 1°, respectively. Additionally, pedalling symmetry between left and right sides could be assumed.

KEY WORDS: cycling, biomechanics, 2D kinematics, 3D kinematics.

INTRODUCTION: A correct bike fitting is very important to practice bicycling in order to avoid injuries and improve performance. The saddle height selection is a main variable of this adjustment. There are static (anthropometry or goniometry) and dynamic methods (kinematic analysis while pedalling) to select the cyclist's saddle height, and dynamic ones are more recommended (Ferrer-Roca et al., 2012).

Two previous studies compared 2D and 3D angular kinematics while pedalling (Umberger and Martin, 2001; Fonda et al., 2014). The first one concluded that both methodologies were valid to measure flexion and extension at the hip, knee and ankle joints in the sagittal plane (Umberger and Martin, 2001). The second one concluded that a low-cost 2D motion capture system (Casio Exilim EX-F1 and Kinovea v 0.8.15) was valid and reliable, much more than the static goniometry. It underestimated the knee extension angle by about 2.2°, but the flexion and extension angles of the others joints were not compared (Fonda et al., 2014).

On the other hand, when performing 2D angular kinematics, most studies analysed only one side, assuming symmetry of motion between left and right sides (Ferrer-Roca et al., 2014; García-López et al., 2016). Edeline et al. (2004) stated that 3D pedalling kinematics is symmetric in all joints except for the ankle. Contrary, García-López et al. (2015) did not find any difference between joints during 2D analyses. Therefore, the main purpose of the present study was to test the validity and sensitivity of a low-cost 2D motion capture system (Casio Exilim EX-ZR1000 and Kinovea v 0.8.24) to analyse angular kinematics in the sagittal plane (trunk, hip, knee and ankle joints) during bicycle pedalling, comparing it with a sophisticated 3D system. Secondly, the 3D kinematics symmetry was also analysed.

METHODS: Twelve well-trained road cyclists participated in this study (26.3±7.7 yr, 68.7±5.0 kg, 178.5±6.1 cm and 8.7 ± 4.6 yr of experience). All of them participated voluntarily, being informed of the procedures, and written consent was obtained before starting the study. The cyclists arrived to the laboratory with their bikes, shoes and clothes. First, their anthropometric characteristics and bikes' measurements were taken (García-López et al., 2016). After this, 20 spherical reflective markers of 10 mm diameter were attached to the skin of the cyclists (at both left and right sides: centre of wrist, lateral humeral epicondyle, posterior acromion, great trochanter, lateral femoral epicondyle, lateral malleolus, lateral aspect of the fifth metatarsal-phalangeal joint and distal part of the calcaneus; the next vertebral apophyses at the spine: C7, D6, L3 and L5-S1), to analyse horizontal-trunk (trunk), horizontal-thigh (hip), knee and ankle joint angles. After a standardized warm-up (5 min at 100 W), the cyclists pedalled 3 sets of 4 min (150 W and 90-100 rpm, with 5 min rest in-between) using three saddle heights in a randomized order (preferred, 2% higher and 2%

lower) (Ferrer-Roca et al., 2014). They pedalled on an indoor cycling trainer (PowerBeam Pro Trainer, Saris Cycling Group, USA). The 3 sets were recorded simultaneously by a sophisticated 3D system (CLIMA C13 series, STT Engineering and Systems, Spain), with six high-speed video cameras (OptiTrack Flex 13, 1280 x 1024 píxels, 120 Hz) (García-Alsina et al., 2005), and by a low-cost 2D system (Kinovea v 0.8.24) with one high-speed video camera (Casio Exilim EX – ZR1000, 640 x 480 píxels, 120 Hz) (Fonda et al., 2014). For the 3D analysis, the whole 30 s after the minute 3 were considered as representative values. For the 2D analysis, three entire cycles of pedalling into the same time interval were considered as representative values. The markers were automatically and manually tracked, respectively. Two-way (system x saddle height) analysis of variance with repeated measures –ANOVA– (Newman-Keuls post hoc analysis) was used to analyze the differences between 3D vs 2D methods, and the sensitivity of these methods to the different saddle heights. One-way ANOVA with repeated measures was used to analyze the differences between both right and left sides of the cyclists. Pearson correlations were performed between the different variables of the study.

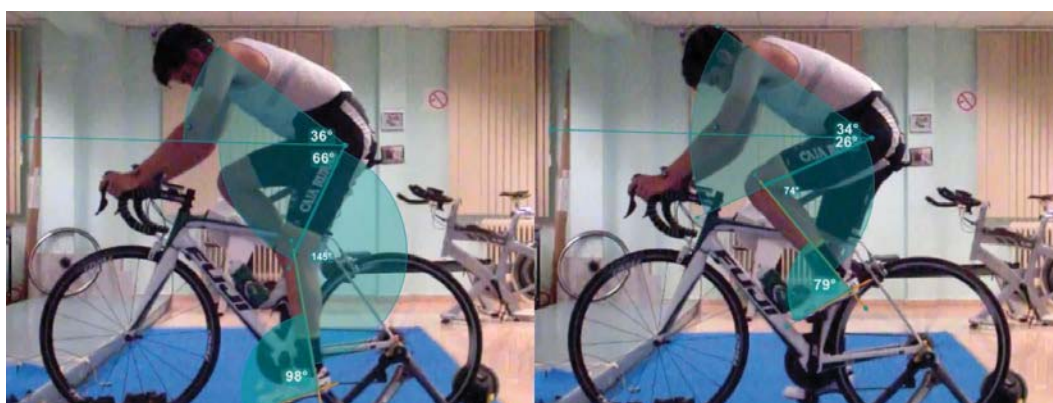


Figure 1: The main angular variables analysed in the present study during the extension (left) and flexion (right) of the pedal cycle (Kinovea v 0.8.24 and Casio Exilim EX – ZR1000).

RESULTS: Taking into account the mean of the three saddle heights, the 2D system underestimated the joint extension ($p < 0.001$) with 2.4° at the knee (143.0 ± 6.7 vs $145.4 \pm 6.6^\circ$) and 2.0° at the hip (143.0 ± 6.7 vs $145.4 \pm 6.6^\circ$), without differences in the ankle (95.4 ± 7.6 vs $95.3 \pm 8.1^\circ$). Moreover, the 2D system also underestimated three joint flexions ($p < 0.001$), 3.4° (20.1 ± 3.3 vs $16.7 \pm 3.3^\circ$), 1.7° (69.6 ± 4.1 vs $67.9 \pm 3.9^\circ$) and 1.2° (75.5 ± 8.5 vs $74.3 \pm 8.3^\circ$), respectively. No significant differences in the mean trunk angle were observed (42.3 ± 3.5 vs $42.6 \pm 3.2^\circ$). Table 1 shows the sensitivity of the 3D and 2D systems to the changes in saddle height. Comparing the lowest and the highest positions, the angles increased ($p < 0.001$) 3.2 and 3.9° at the hip, 7.3 and 7.6° at the knee, 7.4 and 7.9° at the ankle, and 2.0 and 1.7° at the trunk, respectively, without differences between both systems. The differences between both systems (3D vs 2D) did not depend on the positions which were analyzed (preferred, 2% Low and 2% High).

Correlations between both 3D and 2D systems were very high ($p < 0.001$) for the extension at the hip, knee and ankle ($r = 0.96, 0.96$ and 0.92 , respectively), for the flexion at the same joints ($r = 0.91, 0.96$ and 0.93 , respectively), and for the trunk mean angle ($r = 0.91$). Bland-Altman graphs did not show systematic bias between both methods.

Finally, the kinematic variables which were analyzed with the 3D system did not show significant differences between right and left sides ($p > 0.05$). The differences between both sides were always lower than 1° and the coefficients of correlations (r) higher than 0.99 .

Table 1

Mean \pm SD values of the angles (extension and flexion) in the hip, knee, ankle and trunk joints, obtained by a sophisticated 3D vs low-cost 2D systems at the three positions of the saddle (preferred, 2% Low and 2% High).

		3D ANALYSIS			2D ANALYSIS		
		2% Low (°)	Preferred (°)	2% High (°)	2% Low (°)	Preferred (°)	2% High (°)
Hip	Extension	63.4±4.3	64.8±3.9	66.6±3.9	60.3±3.7	62.5±3.6	64.8±3.7
	Flexion	15.6±3.5	16.4±3.2	18.1±2.7	19.0±3.0	19.9±3.1	21.6±3.3
Knee	Extension	141.8±5.9	145.5±5.8	149.1±6.1	139.6±6.2	142.3±5.0	147.2±6.5
	Flexion	66.2±3.6	67.8±3.7	69.8±3.6	67.7±3.8	69.4±3.9	71.6±3.7
Ankle	Extension	91.9±7.9	94.7±7.4	99.3±7.3	91.7±6.8	95.0±6.7	99.6±7.5
	Flexion	72.6±7.9	74.2±8.7	76.0±7.8	74.4±8.6	76.0±8.6	76.0±8.3
Trunk (Mean)		43.3±2.7	43.1±3.0	41.3±3.5	42.9±3.2	42.7±3.2	41.2±3.8

DISCUSSION: The main finding of the present study was that a low-cost 2D analysis system, which was used to obtain flexion and extension angles during bicycle pedalling, was valid and sensitive compared to a sophisticated 3D system. However, the 2D system underestimated both flexion (hip and knee) and extension angles (hip, knee and ankle), without differences in the trunk angle. This is the first study which analysed the flexion and extension differences in all the lower limb joints during pedalling, using a low-cost 2D system. Moreover, symmetry between both right and left sides can be assumed when using this system.

The fundamentals of using 2D systems to analyse bicycle pedalling establish that this movement is performed mainly in the sagittal plane (Umberger and Martin, 2001). The differences in the knee extension angle of the present study (2.4°) are similar to the 2-3° observed in previous studies (Umberger and Martin, 2001; Fonda et al., 2014). However, these authors only considered the “parallax error” as the origin of this difference, when other factors such as the knee movement in the frontal plane must be considered, as we are explaining below. Furthermore, Fonda et al. (2014) only compared the knee extension, while Umberger and Martin (2001) also compared the knee flexion, obtaining similar values (2.2°) to those obtained in the present study (1.7±1.1°). Although these authors also compared the differences between 2D and 3D in the flexion and extension at the hip (32.6 and 33.8°, respectively) and ankle (7.7 and 5.6°, respectively), it seems that different conventions were used, because they are too large. The highest difference observed in the present study was 3.4° at the hip flexion.

From our point of view, the differences between both 2D and 3D systems are due to the combined effect of two factors. First, the “parallax error” could justify why hip and knee flexion angles were underestimated with the 2D system (i.e. the angle values were higher), because the camera was under the axes of both joints (86 cm above the floor). The contrary happened when the joints’ extensions were analyzed (i.e. the angle values were lower in the 2D system), because camera was above the knee and ankle joints. Second, during the propulsive phase of pedalling (0-180°), the knee adduction is between 2-3 cm (Ruby et al., 1992), and the hip and knee extensions were analyzed in this phase. Therefore, the projected angle in the sagittal plane is lower (i.e. 2D system) than the real angle (i.e. 3D system). The ankle extension angle did not change between the two systems because the “parallax error” compensated the effect of the knee adduction. A similar compensation was observed when comparing the trunk angle, but in this case the angle was equal in the two systems because the shoulders were in abduction with respect to the hips although the hips were above the camera.

The correlations between both systems (i.e. 2D and 3D) were very high, and the differences in-between did not depend on the angle value. However, according to previous studies, a difference of 1 cm in saddle height could change the knee extension angle 2-3°, and 1-2° the

hip flexion-extension and knee flexion angles (Ferrer-Roca, et al., 2014). This highlights the relevance of correcting the angles when comparing the data obtained by 2D and 3D systems. On the other hand, the sensitivity of changing 4% the saddle height (low vs high positions, Table 1) was similar to the observed in previous studies (Ferrer-Roca, et al., 2014). The change in the mean trunk angle (1.7-2.0°) was due to the no modification of the handlebar when raising the saddle.

Finally, the second purpose of the present study was to test the symmetry between the right and left sides from a kinematical point of view. When comparing both sides using the 3D system, no significant differences were found. These results agree with those obtained in a previous 2D study (García-López et al., 2015), but are contrary to other 3D study (Edeline et al, 2004). It could be possible that in this last study the characteristics of the participants (i.e. non-cyclists) affected the symmetry. So, at this moment, the pedalling in experienced cyclists can be considered symmetric from a kinematical point of view.

CONCLUSION: The most important conclusion of the present study is that a low-cost 2D analysis system of bicycle pedalling is valid and sensitive enough to detect small changes in saddle height when comparing with respect to a sophisticated 3D system. The differences between both systems are relevant and must be corrected to interchange data between 2D and 3D: the extension of the hip and knee joints are 2-3° lower and the flexion of the hip, knee and ankle joints are 4 to 1° lower, respectively. These differences do not depend on the angle value, and the trunk angle could be interchangeable between both systems. Additionally, when performing 2D analysis, pedalling symmetry between both right and left sides can be assumed.

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