

Testing the Planar Assumption During Ergometer Cycling

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Lower extremity motions during cycling are often assumed to occur in the sagittal plane. While seemingly logical, this assumption has not been rigorously tested. Frontal plane rotation of the ankle joint (inversion/eversion) has been studied extensively during gait but infrequently during cycling despite the suggestion that excessive eversion or pronation may be related to overuse knee injuries. Two-dimensional sagittal plane hip, knee, and ankle joint kinematics were generally found to be similar to simultaneously measured 3-D values. Despite the similarity in motion patterns, maximum hip angle was 34° more flexed in 2-D than 3-D. Maximum and minimum frontal plane ankle joint angles were similar in 2-D and 3-D. However, during the middle of the pedal cycle, 2-D frontal plane ankle joint motion deviated from 3-D, such that maximum ankle eversion was reached 36% of the pedal cycle later in 2-D versus 3-D. The discrepancy at the hip was due primarily to differences in hip angle definition for 2-D and 3-D approaches, and an alternate convention for hip angle in 2-D is suggested. Discrepancies in frontal plane ankle joint motion are due to weaknesses in the planar approach and would be difficult to overcome without resorting to 3-D measurement.

Key Words: kinematics, 2-D, 3-D, pedaling

Introduction

The rhythmic limb movements of cycling are generally considered to occur in the sagittal plane and have frequently been modeled as such (Broker & Gregor, 1994; Hull & Jorge, 1985; Marsh, Martin, & Sanderson, 2000; Umberger, Scheuchenzuber, & Manos, 1998). A sagittal plane model ignores motion that occurs outside the plane being studied, and separate analyses would need to be conducted for the frontal and transverse planes. Two-dimensional (2-D) frontal and transverse plane assessments of lower limb joint motion during cycling are not common, and would be difficult to conduct in many cases (e.g., measurement of transverse plane knee joint rotation using a single camera). Additionally, the motion being studied may not be accurately represented if it deviates from the actual plane of analysis. The only way to determine how well a planar model represents actual

joint motion in a given plane is to compare planar measurements with three-dimensional (3-D) data. No complete account of lower limb motion in 3-D during cycling has been reported in the scientific literature. Two-dimensional sagittal plane models have been used extensively in cycling; however, 2-D frontal plane models have been limited to use in other forms of locomotion (e.g., running; Edington, Frederick, & Cavanagh, 1990). The accuracy with which frontal plane ankle joint kinematics during cycling can be measured in 2-D would be of interest, as excessive eversion or pronation has been suggested as a cause of knee injuries in cycling (Francis, 1988). The purpose of this study was to test the assumption that 2-D models adequately represent sagittal and frontal plane lower extremity motion during cycling.

Methods

Four experienced male cyclists ($\bar{X}_{\text{age}} = 27.5 \pm 4.8$ years, $\bar{X}_{\text{ht}} = 1.73 \pm 0.05$ m, $\bar{X}_{\text{mass}} = 68.9 \pm 4.1$ kg) pedaled on a Velodyne ergometer under controlled power (225 W) and cadence (90 rpm) conditions. Seat height was matched to the subjects' own bicycle ($\bar{X}_{\text{seat}} = 104.4 \pm 1.2\%$ greater trochanter height). Subjects wore snug fitting cycling shoes and used clipless pedals that allowed several degrees of motion about an axis normal to the pedal surface.

Four 60 Hz S-VHS video cameras were used for data collection (Figure 1). The cameras were synchronized using timing lights accurate to 0.001 s, placed in view of all cameras. An additional light was illuminated each time the left crank reached top dead center (TDC). Cameras 3 and 4 provided the basis for the 2-D sagittal plane and 2-D frontal plane analyses, respectively. Camera 4 was placed 12 m behind the subject, raised to a height of 3 m, and then angled down to more closely match the plane of the shank and calcaneus during the downstroke (Figure 1B). In cycling, most of the power is delivered to the pedals during the downstroke from TDC to bottom dead center (Broker & Gregor, 1994). Thus, the exact position of camera 4 was chosen such that it was aligned with an intermediate plane of motion for the leg and foot occurring during the downstroke, thereby providing the best possible estimate of rearfoot motion in 2-D.

Spherical, reflective markers were adhered to the skin or clothing over anatomical landmarks on the pelvis and left lower limb (Vaughan, Davis, and O'Connor, 1992, p. 23). A marker was also placed on the shoulder for determination of 2-D sagittal plane hip angle using a shoulder-hip-knee convention. An alternative 2-D hip angle was also computed using markers on the pelvis and femur only, as is done in the 3-D approach (see the appendix). Two markers each were placed on the posterior shank and rearfoot for determination of 2-D ankle inversion/eversion (Nigg, 1986, p. 42). Three-dimensional marker coordinates were calculated using the direct linear transformation method (Abdel-Aziz & Karara, 1971). Resultant mean error of reproduction for 20 control points was ≤ 1.4 mm. Raw coordinate data were smoothed using a fourth-order Butterworth digital filter with cutoff frequencies individually determined (3 to 6 Hz) for each coordinate of each marker (Jackson, 1979).

The orientation of a distal segment relative to the adjacent proximal segment was expressed using a joint coordinate system (Cole, Nigg, Ronsky, & Yeadon, 1993; Grood & Suntay, 1983). Angular position values were computed for flexion/extension, abduction/adduction, and medial/lateral rotation (hip and knee), or plantar/dorsiflexion, abduction/adduction, and inversion/eversion (ankle). From the 2-D views, sagittal plane hip and knee flexion/extension, and ankle plantar/dorsiflexion were determined, as well as frontal plane ankle inversion/eversion. These 2-D values were the specific variables that were contrasted with their 3-D counterparts. Joint angle curves, expressed from TDC to next

TDC, were normalized to 100% of the pedal cycle and averaged across three consecutive pedal cycles. Cross-correlation analyses were used to quantify the degree of agreement in the shape of two corresponding curves.

Results

Cross correlation coefficients for the sagittal plane hip, knee, and ankle kinematics all approached unity, denoting the similarity between movement patterns in 2-D and 3-D (Table 1). The correlation for ankle inversion/eversion was lower (0.65) than for the sagittal

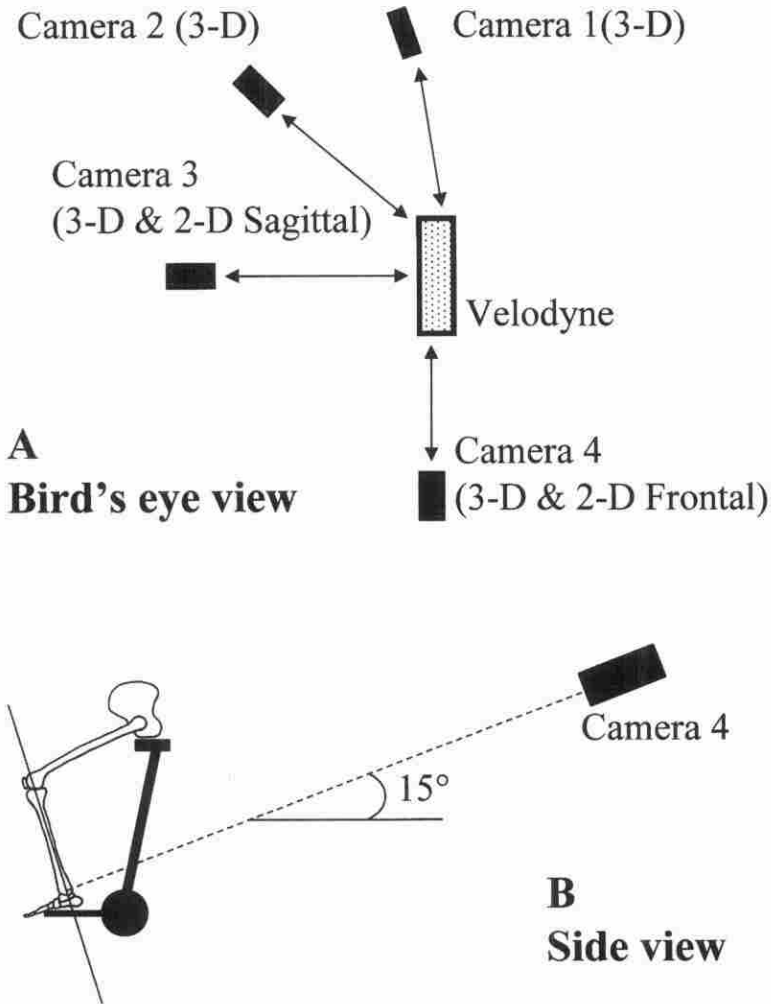


Figure 1 — Diagrammatic representation of camera arrangement. Distances are not to scale. (a) Position of all four cameras relative to the ergometer and subject. Subject is facing toward top of page. (b) Position and orientation of camera 4 relative to the shank and foot during the downstroke.

Table 1 Cross Correlation Coefficients (R_{xy}), Maximum and Minimum Joint Angles, and the Point in the Pedal Cycle at Which the Maximum and Minimum Joint Angles Occurred

Variable	Maximum angle (°)	Maximum angle % pedal cycle	Minimum angle (°)	Minimum angle % pedal cycle	R_{xy}
3-D hip (sagittal)	86.4	0	39.4	48	
2-D hip (sagittal)	119.0	6	73.2	52	0.97
2-D hip alt (sagittal)	74.2	6	38.1	52	0.97
3-D knee (sagittal)	114.0	94	40.1	42	
2-D knee (sagittal)	111.8	96	42.4	46	0.98
3-D ankle (sagittal)	0.1	50	-16.1	16	
2-D ankle (sagittal)	7.8	52	-10.5	18	0.98
3-D ankle (frontal)	1.0	16	-5.4	48	
2-D ankle (frontal)	0.6	26	-5.1	84	0.65

Note. 2-D hip alt is the sagittal plane hip joint angle calculated using markers on the pelvis and femur only. R_{xy} is the correlation coefficient between a 2-D curve and the corresponding 3-D curve.

tal plane comparisons. With the exception of the 2-D hip joint angle and the timing of maximum ankle eversion, 2-D angle extrema were generally within 10° of the 3-D angles and occurred within 10% of the pedal cycle of each other (Table 1). Three-dimensional joint angle data exhibited low intersubject variability at all three joints for most planes of motion (Figure 2). The 2-D hip angle based on the shoulder-hip-knee convention consistently overestimated the 3-D hip joint angle by approximately 30° (Figure 3A). Use of the pelvis-femur convention for the 2-D hip angle improved the agreement in magnitude between the 2-D and 3-D hip joint curves. Two-dimensional and 3-D patterns of motion were similar for the ankle eversion angle during the first and last 25% of the pedal cycle, but deviated considerably during the middle of the pedal cycle (Figure 3D).

Discussion

The pedaling motion is usually modeled as a planar activity (Broker & Gregor, 1994; Hull & Jorge, 1985; Marsh et al., 2000; Umberger et al., 1998). Three-dimensional joint rotations of the lower limb (Figure 2) confirm that cycling is predominately a sagittal plane

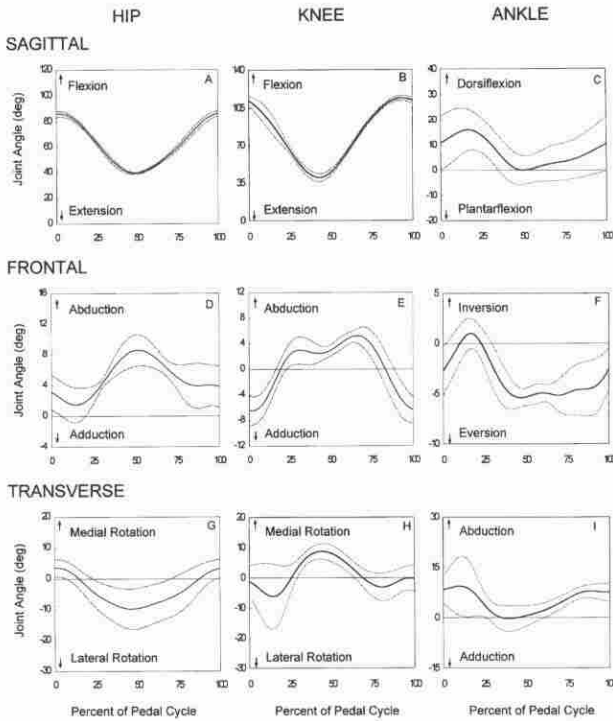


Figure 2 — Ensemble average sagittal (a, b, and c), frontal (d, e, and f), and transverse (g, h, and i) plane rotations of the hip, knee, and ankle joints, respectively, during pedaling on a bicycle ergometer. Dashed lines represent ± 1 SD. Top dead center corresponds to 0 and 100% of the pedal cycle.

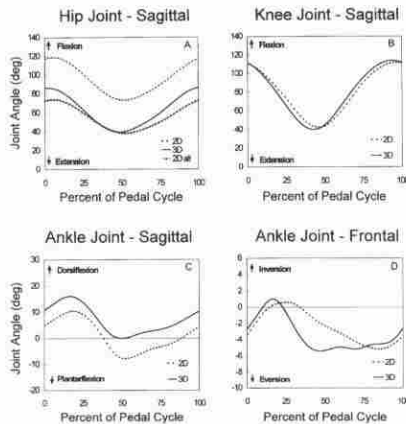


Figure 3 — Ensemble average sagittal plane rotations of the hip (a), knee (b), and ankle (c) joints, and frontal plane ankle joint inversion/eversion (d) measured in 2-D and 3-D during pedaling on a bicycle ergometer. The planar hip angles (a) were calculated using a shoulder-hip-knee convention (2-D) and a pelvis-femur convention (2-D alt). Note the large but consistent offset between 2-D and 3-D for the hip (a) using the shoulder-hip-knee convention, and the deviation between 2-D and 3-D for ankle inversion/eversion (d) in the middle of the pedal cycle. Top dead center corresponds to 0 and 100% of the pedal cycle.

activity. Sagittal plane ranges of motion of all three joints were quite large (15 to 70°), while non-sagittal plane ranges of motion were usually $\leq 10^\circ$. However, noticeable differences between 2-D and 3-D representations are apparent in the sagittal plane for the hip (Figure 3A) and frontal plane for the ankle (Figure 3D). The importance, implications, and origins of these two discrepancies are quite different.

Sagittal plane motion patterns at the hip joint measured in 2-D and 3-D were similar, but the magnitudes of the 2-D sagittal plane joint angles were higher (more flexed) using the shoulder-hip-knee convention than the 3-D representation. This likely results from the trunk segment being represented by a line connecting the hip joint and the shoulder joint in 2-D. Thus, any flexion in the vertebral column or protraction of the shoulder girdle will be recorded as hip flexion. For 3-D, orthonormal reference frames are established in the pelvis and thigh, from which the hip angle is determined. Therefore, only positions of the pelvis and femur are included in calculating the hip joint angle in 3-D. A more accurate representation of the 3-D sagittal plane hip joint angle can be obtained in 2-D by following the procedures outlined in the appendix. We recommend that the pelvis-femur based definition of the 2-D sagittal plane hip joint angle be used in future cycling studies. However, in the event that only derivatives of joint angular position are required, such as for an inverse dynamics analysis, the similarity in shape of both 2-D approaches should result in similar angular velocity and acceleration values. Indeed, the peak angular velocities for hip extension (as well as knee extension and ankle plantarflexion) calculated in 2-D and 3-D differed by less than 10% and occurred within 4% of the pedal cycle of each other.

Two-dimensional and 3-D representations of the ankle inversion/eversion angle showed more serious kinematic differences. The primary difference was a deviation of the two curves beginning at approximately 25% of the pedal cycle, rather than a simple offset across the full pedal cycle (Figure 3D). This error is especially relevant, as that is the portion of the pedal cycle where most eversion occurs, pedal forces are highest (Hull & Jorge, 1985), and most of the power is delivered to the pedal (Broker & Gregor, 1994). Rapid eversion beginning at 25% of the pedal cycle was coincident with rapid medial rotation of the shank (Figure 2H) relative to the thigh, which is the mechanism suspected to be associated with overuse knee injuries (Francis, 1988). The rate and extent of ankle eversion during the downstroke would be underestimated by relying on 2-D measurements. Differences between 2-D and 3-D are likely due to variable amounts of perspective error over the pedal cycle, coupled with the non-frontal plane motions at the ankle joint during the downstroke (Figure 2C and 2I). This deviation occurred despite our efforts to define a camera orientation that minimized perspective error. A substantial difference was also found for the velocity of eversion (or pronation), a variable often calculated to describe rearfoot kinematics. The maximal velocity of eversion for 3-D was twice the value (40.9 vs. 20.5°/s) for 2-D and occurred earlier in the pedal cycle. If one wants an accurate description of the kinematic behavior of the ankle joint complex, 3-D appears to be the only reasonable option.

A limitation of the present investigation was the use of only 4 subjects. Despite the small sample size, intersubject variability in joint motion patterns was generally low, as reflected by the standard deviation envelopes (Figure 2). The small standard deviation values are likely a direct result of the constrained nature of the pedaling motion and lend support to the validity of our conclusions. Another limitation was the implicit use of our 3-D data, derived from surface markers, as the "gold standard" for comparison with 2-D data. Other investigators (Reinschmidt et al., 1997a, 1997b) have shown differences in knee and ankle joint kinematics obtained from bone markers and surface markers during running, with much of the error attributed to movement of markers on the thigh and shoe,

respectively. Although the amount of error in the present investigation due to the use of surface markers cannot be determined, we suspect the error in cycling to be less than in running due to the lack of an impact phase and the use of snug fitting cycling shoes.

Overall, 2-D sagittal plane kinematics during cycling were similar to the respective angles measured in 3-D. The two most notable kinematic differences existed in the sagittal plane hip joint and frontal plane ankle joint motions. The offset between 2-D and 3-D at the hip joint can be minimized by defining a pelvic segment in 2-D, as described in the appendix. The frontal plane deviations between 2-D and 3-D at the ankle joint are of greater concern and suggest that a planar analysis can at best provide a qualitative picture of rearfoot motion during cycling. A 3-D approach may be needed to adequately describe typical variables of interest at the ankle joint complex and for the ankle inversion/eversion angle in particular.

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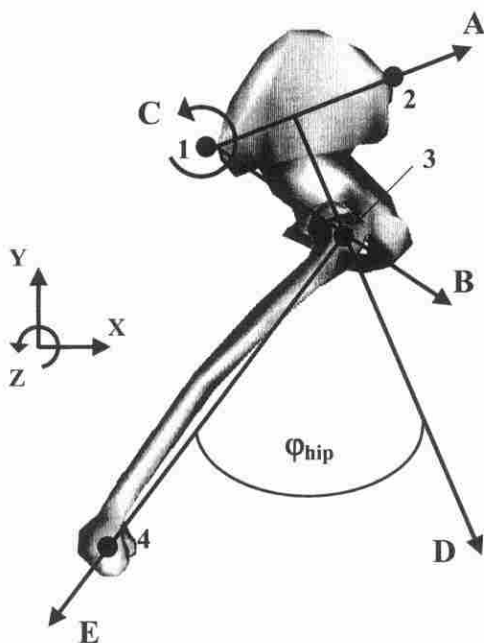


Figure 4—Alternative definition of the sagittal plane hip joint angle, measured in 2-D. Markers are placed over the anterior superior iliac spine, posterior superior iliac spine or sacrum, greater trochanter, and lateral femoral condyle. The determination of vectors A–E, and ϕ_{hip} are described in the appendix. Bone images are courtesy of Scott Delp, and are available from the International Society of Biomechanics web site <<http://isb.ri.ccf.org/>>.

Appendix

Sagittal plane hip joint angle in cycling has generally been defined using markers on the shoulder, greater trochanter, and lateral femoral condyle. An alternative definition is presented using markers on the pelvis and femur only. Markers are placed on the anterior superior iliac spine (marker 1), posterior superior iliac spine or sacrum (marker 2), greater trochanter (marker 3), and lateral femoral condyle (marker 4; Figure 4). Vectors **A** and **B** run from marker 1 to marker 2 and marker 1 to marker 3, respectively. Vectors **C** and **D** are defined as follows:

$$\mathbf{C} = \mathbf{B} \times \mathbf{A} \text{ and } \mathbf{D} = \mathbf{A} \times \mathbf{C},$$

and **E** is a vector running from marker 3 to marker 4. Hip joint angle (ϕ_{hip}) is computed as

$$\phi_{hip} = \cos^{-1}(\hat{\mathbf{d}} \cdot \hat{\mathbf{e}}) \quad (\text{A1})$$

where $\hat{\mathbf{d}}$ and $\hat{\mathbf{e}}$ are unit vectors in the directions of **D** and **E**, respectively. Note that **D** as calculated above does not, in general, pass through the hip joint (Figure 4), but this does not affect ϕ_{hip} . Equation (A1) is only valid from full hip extension to maximal hip flexion; however, as full extension is rarely achieved during cycling no problems should arise from this limitation.

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