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Methods for Determining Hip Movement in Seated Cycling and Their Effect on Kinematics and Kinetics

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In a previous paper (Neptune & Hull, 1995), a new video-based method (ASIS) for locating the hip joint center (HJC) in seated cycling was shown to be more accurate than tracking a marker placed over the superior aspect of the greater trochanter (TRO). The main goal of the present study was to see if the conclusions presented in Neptune and Hull (1995) may be applied to other cyclists. Lower limb kinematic and pedal force data were collected from 7 cyclists at nine combinations of pedaling rate and work rate. ASIS produced significantly different hip joint movement patterns than TRO, which resulted in significantly different power and work calculations developed by the intersegmental hip joint force, at all combinations except one. A significant quadratic trend was evident as a function of pedaling rate, and a significant linear trend was evident for work rate. At naturally preferred pedaling rates (~90 rpm) and lower work rates (<225 W), the hip joint movement was minimum. Under these conditions, the fixed hip assumption is least prone to error.

Biomechanical analyses in cycling research are often performed using inverse dynamics. Essential to solving the inverse dynamics problem is determination of lower extremity kinematics. There are two general methods used to determine kinematics: analytical equations based on geometry and the kinematic data of the pedal and crank arm (Hull & Jorge, 1985), and video analysis of skin markers placed over the joint centers (Gregor, Broker, Ryan, & Margaret, 1991). Whether the researcher uses either the analytical equations or the video-based method to compute lower extremity kinematics, the accuracy of the data ultimately affects biomechanical quantities (i.e., intersegmental moments, joint powers, and joint works) computed by the inverse dynamics solution. Although hip joint center (HJC) kinematics are most often measured using video analysis, inaccuracies exist in determining HJC and hence biomechanical quantities because of the anatomical location of the joint center and soft tissue surrounding this region.

A new method was presented by Neptune and Hull (1995) to increase accuracy of locating the HJC by reducing errors associated with soft tissue movement over bony landmarks. The new method (ASIS) located the HJC by attaching a vector of fixed magnitude and orientation to a video marker located over the palpable anterior–superior iliac spine. A standard method (STD) was developed to provide a platform to compare ASIS with two frequently used methods in cycling research, the fixed hip (FIX) method (e.g., Hull &

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Gonzalez, 1990) and the trochanter (TRO) method (e.g., van Ingen Schenau, Van Woensel, Boots, Snackers, & deGroot, 1990). STD involved establishing a pelvis-fixed coordinate system using a triad of video markers attached to an intracortical pin. The pelvis-fixed coordinate system movement was recorded using three-dimensional motion analysis to quantify the true HJC position coordinates. These data were then compared with data from the other three methods, which produced three noteworthy results.

First, ASIS had less error than TRO primarily due to less marker movement. The increased marker movement of TRO was attributed primarily to soft tissue error. A comparison with STD illustrated an increase in accuracy of computing biomechanical quantities with ASIS due to this decrease in movement error.

A second result was that the fixed hip assumption is also prone to error because it ignores the true HJC movement. The biomechanical quantity most affected by this assumption is the power developed by the intersegmental hip joint force. The intersegmental hip joint force (or hip joint force, for brevity) is the net internal reaction force that is the vector sum of all forces transmitted by muscles, ligaments, and bones across the intersegmental joint. The hip joint force is only capable of redistributing power from the pelvis to the thigh segment (Aleshinsky, 1986a, 1986b; van Ingen Schenau et al., 1990). The power redistributed from the pelvis is the result of upper extremity joint torques (Kautz, Hull, & Neptune, 1994). Assuming a fixed HJC, the velocity at the joint center is zero, thus producing zero hip joint force power. The subject of Neptune and Hull (1995), using STD at 90 rpm and 225 W, produced a peak hip joint force power of 12.24 W, thus indicating the degree of error introduced in joint power calculations using FIX. The magnitude of this error can increase with higher pedaling rates and work rates that produce higher power generation by the hip joint force. But when hip joint force work was computed, FIX was the most accurate method by assuming zero work since the errors associated with ASIS and TRO were larger by at least a factor of 2. These results were important since the computation of hip joint force work produced over the crank cycle influences the accuracy of mechanical energy expenditure calculations (e.g., van Ingen Schenau et al., 1990).

The third result of Neptune and Hull (1995) indicated that there was no relationship between either the accuracy of hip joint force power and work or the magnitude of HJC movement with protocol for the subject tested. As pedaling rate and work rate were increased, no corresponding increase in HJC movement was detected. However, it was noted that the magnitude of hip joint movement in the vertical direction was always a minimum at the 90 rpm pedaling rate, independent of work rate. Further, the magnitudes of movement in both the horizontal and vertical directions exhibited overall minima at the 90 rpm and 225 W combination. At this combination, errors in computed biomechanical quantities using FIX were comparable to those errors using ASIS. Accordingly, for this restricted protocol, FIX was a viable method for describing hip movement.

Although these results both support the implementation of ASIS as the best method to track HJC movement over a broad range of cycling protocols and indicate that FIX may be useful for restricted biomechanical quantities and protocols, the results were only applicable to the subject tested. Because cycling mechanics and soft tissue movement are cyclist dependent, the primary goal of the present paper was to examine a group of 7 cyclists to see if the results of Neptune and Hull (1995) might be applied to them. The first objective was to test the hypothesis that ASIS produces significantly different movement patterns than TRO over a broad spectrum of cycling protocols and compare these movement differences with the subject of Neptune and Hull (1995). To assess the impact that movement differences may have on kinetic quantities, a second objective was to test the hypothesis that ASIS and TRO produce significantly different magnitudes of hip joint force power and work. Finally, to establish the conditions under which the fixed hip assumption (FIX) may be appropriate, a third objective was to identify those pedaling rate and work rate combinations that produce the minimum HJC movement.

Methods

Seven male cyclists (mean height = 1.8 ± 0.07 m; mean weight = 69.9 ± 7.5 kg; mean age = 22.9 ± 3.1 years) viewed as a random sample from a population of competitive cyclists volunteered for participation in this study. Informed consent was obtained before the experiment. The subjects rode a conventional racing bicycle mounted on a Velodyne cycling ergometer. The bicycle configuration was adjusted to match the geometry of each subject's own bicycle, so that seat and handlebar heights were not controlled.

Hip joint kinematics were analyzed using both TRO and ASIS recorded simultaneously on the right leg using video analysis. The methodology of TRO and ASIS is identical to Neptune and Hull (1995) and will be reviewed briefly here. TRO located the HJC by placing a spherical marker over the superior aspect of the greater trochanter when the crank arm was in the forward horizontal position. The results of Neptune and Hull (1995) indicated that the forward horizontal position corresponds to the average spatial coordinates of the greater trochanter.

ASIS determined the position of the HJC from the anterior–superior iliac spine. A vector of fixed magnitude and orientation in the sagittal plane was established by computing the vector between the average anterior–superior iliac spine and average trochanter marker coordinates. The vector was added to the anterior–superior iliac spine marker coordinates to locate the HJC. The video data for both methods were processed to produce a time history of the HJC horizontal and vertical components.

To provide data for FIX, the HJC position was located by external anthropometric measurements from the laboratory coordinate system origin fixed at the center of the crank spindle to the superior aspect of the greater trochanter. The measurements were taken after a warm-up period with the crank arm positioned in the forward horizontal position.

The biomechanical quantities were computed using a standard inverse dynamics approach identical to that used by Neptune and Hull (1995). The rider was modeled as a five-bar linkage in plane motion. The equations of motion for each link were solved using inverse dynamics, starting with the foot and proceeding through each link to the hip. The anthropometric estimates of each segment's mass and center of gravity were defined based on the work of Dempster (1955). Moments of inertia were computed by the data presented in Whittsett (1963), which were personalized to each subject based on the work of Dapena (1978). The necessary kinematic data were recorded from reflective markers located over the right lateral epicondyle, lateral malleolus, pedal spindle, and crank spindle. These markers were videotaped simultaneously with the two hip markers at 60 Hz. Angular orientation data of the crank arm and pedal were collected simultaneously with two optical encoders sampled at 100 Hz. Both the video and encoder data were filtered using a fourth-order, zero phase shift, Butterworth low-pass filter with a cutoff frequency of 9 Hz. All derivatives to determine coordinate velocity and acceleration were calculated by fitting a quintic spline to the position data and differentiating the resulting equations.

The pedal force data were collected simultaneously with the video and encoder data using a pedal dynamometer similar to that described by Newmiller, Hull, and Zajac (1988), which was modified to allow subjects to wear conventional clip-in cycling shoes. Weight was added to the opposite pedal to balance the inertia of the pedals. The pedal force data were filtered using a fourth-order, zero phase shift, Butterworth low-pass filter with a cutoff frequency of 20 Hz. The filtered pedal force and encoder data were linearly interpolated to correspond in time with the video coordinate data.

The protocol, which was identical to that of Neptune and Hull (1995), consisted of a 10-min warm-up period at a work rate of 120 W at 90 rpm. Each subject cycled at power levels of 150, 225, and 300 W and pedaling rates of 60, 90, and 120 rpm. The accuracy of control was maintained at ±1 rpm and ±5 W. All three pedaling rates were performed at each of the three work rates, yielding nine combinations of pedaling rate and work rate. These combinations were randomly assigned using a random number table to control for possible interactions and fatigue. After a 2-min adaptation period, data collection was randomly initiated during the third minute for 10 s.

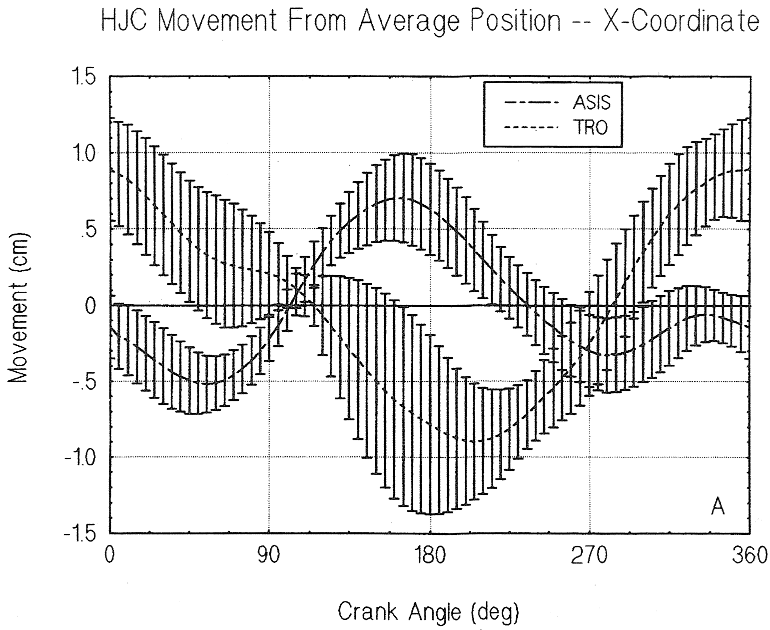
To satisfy the stated objectives, the statistical analysis consisted of three steps using a repeated-measures design since each combination of pedaling rate and work rate was assigned to each subject. First, a three-factor analysis of variance was performed to detect significant differences between ASIS and TRO in measured HJC movement over the nine combinations of pedaling rate and work rate. When significant differences did exist, a second one-factor analysis of variance was performed at each combination of pedaling rate and work rate to detect which combinations were significantly different ($p < .05$). To compute the movement associated with each method, the average value of the HJC coordinates was subtracted from the coordinate data. The range of movement for each of the eight cycles of data was computed and averaged for each cyclist. The average range of movement for all subjects was then computed and used as the dependent variable in the analysis of variance. Second, a three-factor analysis of variance was performed to detect significant differences between ASIS and TRO in computed peak hip joint power and work over the full crank cycle for the nine combinations of pedaling rate and work rate. Again, when significant differences did exist, a second one-factor analysis of variance was performed to detect which combinations were significantly different ($p < .05$). Third, an analysis of variance polynomial contrast was performed on pedaling rate and work rate to detect significant linear and quadratic trends in hip movement as a result of increased pedaling rate and work rate ($p < .05$).

Results

The HJC coordinates averaged over all subjects and plotted as a function of crank angle illustrate the movement and phasing differences between ASIS and TRO at the 90 rpm, 225 W combination (Figure 1, a and b). In the X-direction (horizontal), the patterns of movement were fundamentally different, with ASIS exhibiting a two-cycle pattern and TRO a single-cycle pattern. The movement range of TRO was about 50% greater than that of ASIS. Although the patterns of movement were similar in the Z-direction (vertical), with extreme values occurring in phase, the range of movement of TRO was about 150% greater than that of ASIS. Thus, marked differences in movement between the two methods were apparent in both coordinates.

Analysis of variance detected a significant difference in HJC movement in both coordinate directions between ASIS and TRO over the nine combinations of pedaling rate and work rate ($p < .0001$). Therefore, the null hypothesis that TRO and ASIS produced the same magnitude of hip motion over a broad spectrum of cycling protocols was rejected. Further, statistical analysis at each combination of pedaling rate and work rate detected significant differences in the X-coordinate at the 150 W work rate and at every combination of pedaling rate and work rate in the Z-coordinate (Tables 1 and 2) ($p < .05$).

The magnitude of HJC movement produced by ASIS significantly increased in both coordinate directions with increased work rate ($p < .05$) (Table 3). The movement



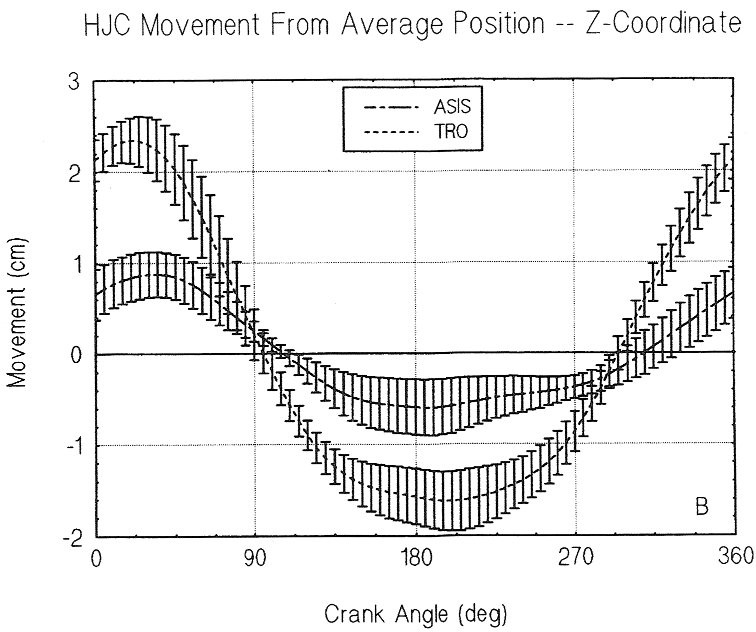


Figure 1 — Hip joint center (a) X-coordinate and (b) Z-coordinate movement from the average position as a function of crank angle for 7 subjects (90 rpm, 225 W). Error bars represent ±1 standard deviation.

Table 1 Method Comparison of X-Coordinate Range of Movement as a Function of Pedaling Rate and Work Rate (cm)

		Work rate					
		150 W		225 W		300 W	
		M	*SD*	*M*	*SD*	*M*	*SD*
60 rpm	$ASIS_x$	1.39	0.35	1.91	0.47	2.48	0.52
	TRO_x	2.17*	0.45	2.32	0.60	2.25	0.57
90 rpm	$ASIS_x$	1.43	0.40	1.51	0.36	1.79	0.35
	TRO_x	2.33*	0.78	2.12	0.53	2.36	0.73
120 rpm	$ASIS_x$	1.62	0.29	1.60	0.35	1.91	0.36
	TRO_x	2.30*	0.58	2.20	0.65	2.14	0.71

*Significantly different ($p < .05$).

Table 2 Method Comparison of Z-Coordinate Range of Movement as a Function of Pedaling Rate and Work Rate (cm)

		Work rate					
		150 W		225 W		300 W	
		M	*SD*	*M*	*SD*	*M*	*SD*
60 rpm	$ASIS_z$	1.73	0.44	1.93	0.49	2.28	0.73
	TRO_z	4.15*	0.75	4.24*	0.82	4.33*	0.71
90 rpm	$ASIS_z$	1.34	0.41	1.60	0.49	1.79	0.71
	TRO_z	3.83*	0.55	4.05*	0.54	4.32*	0.94
120 rpm	$ASIS_z$	1.87	0.48	1.95	0.45	2.43	0.57
	TRO_z	4.45*	0.53	4.42*	0.57	4.94*	0.72

*Significantly different ($p < .05$).

produced by TRO also increased in the Z-direction but not in the X-direction. HJC movement tabulated as a function of pedaling rate revealed a significant quadratic trend with a minimum at 90 rpm for both methods in the X- and Z-coordinate directions except for TRO X-direction, which remained relatively constant.

The pedaling and work rates that produced the minimum HJC movement varied among coordinates. The minimum movement for the X-coordinate occurred at 60 rpm, 150 W and at 90 rpm, 225 W for ASIS and TRO, respectively (Table 1). The minimum movement for the Z-coordinate was produced at the 90 rpm and 150 W combination for both methods (Table 2).

Marked differences in the computed hip joint force power between ASIS and TRO were apparent at the 90 rpm, 225 W combination (Figure 2). Statistical analysis detected

Table 3 Trend Comparison of Hip Joint Center Range of Movement as a Function of Pedaling Rate and Work Rate (cm)

	Work rate					
	150 W		225 W		300 W	
	M	*SD*	*M*	*SD*	*M*	*SD*
$ASIS_x$†	1.48	0.35	1.67	0.39	2.06	0.41
$ASIS_z$†	1.65	0.44	1.83	0.48	2.17	0.67
TRO_x	2.27	0.61	2.21	0.59	2.25	0.67
TRO_z†	4.14	0.61	4.24	0.64	4.53	0.79
	Pedaling rate					
	60 rpm		90 rpm		120 rpm	
	M	*SD*	*M*	*SD*	*M*	*SD*
$ASIS_x$*	1.93	0.45	1.58	0.37	1.71	0.33
$ASIS_z$*	1.98	0.55	1.58	0.54	2.08	0.68
TRO_x	2.25	0.54	2.27	0.68	2.21	0.64
TRO_z*	4.24	0.76	4.06	0.67	4.60	0.61

†Significant linear trend ($p < .05$). *Significant quadratic trend ($p < .05$).

significant differences in peak hip joint force power between ASIS and TRO over the broad spectrum of protocols ($p < .0001$). Therefore, the null hypothesis that the three methods produced equal magnitudes of hip joint force power was rejected. Analysis at each combination of pedaling rate and work rate detected significant differences between the two methods at every combination except at 60 rpm, 300 W (Table 4). TRO had the largest peak power at all pedaling and work rates (Table 4), which is consistent with the overestimates of TRO by Neptune and Hull (1995). The overestimate produced by TRO existed throughout the entire crank cycle and was quantified by the integral of the power curve resulting in the work produced by the hip joint force. The statistical analysis detected significant differences in hip joint force work between ASIS and TRO over the spectrum of protocols, thus rejecting the null hypothesis that the two methods produced equal magnitudes of hip joint force work. Significant differences were detected at all combinations of pedaling and work rate except at 120 rpm and 150 W (Table 5).

Discussion

Neptune and Hull (1995) examined three methods used to track the HJC during steady-state seated cycling: the ASIS, FIX, and TRO methods. The results of Neptune and Hull (1995) indicated that ASIS was the most accurate in tracking HJC movement for the subject studied. TRO had substantially greater soft tissue movement errors, thus exaggerating the importance of hip movement, whereas FIX produced errors by ignoring the movement of the HJC altogether. However, at the preferred cadence of 90 rpm and 225 W, the hip

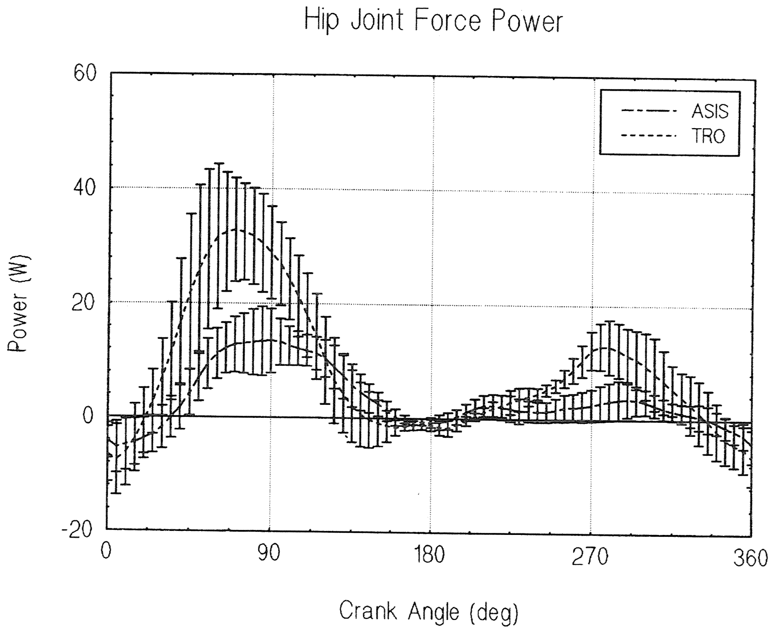


Figure 2 — Hip joint force power as a function of crank angle for 7 subjects (90 rpm, 225 W). Note that the peak values for each method occur at different points in the crank cycle. Error bars represent ±1 standard deviation.

movement was minimum, therefore establishing the propriety of the fixed-hip assumption under this restricted protocol for the subject tested. These results were important in the quest for improved accuracy of cycling data but were interpreted with caution since data were collected for only 1 subject. Thus, the general objective of the present paper was to determine the applicability of the results of Neptune and Hull (1995) to typical subjects used in cycling biomechanics research.

To satisfy this general objective, the hypothesis that ASIS produces a different range of movement than TRO was tested using a repeated-measures design. The null hypothesis that the ranges of movements of the two methods are equal in magnitude was rejected in both coordinate directions. Further analysis detected significant differences in the vertical direction at all pedaling and work rate combinations and in the horizontal direction for all pedaling rates at the 150 W work rate, with the range of movement of ASIS being significantly lower in both coordinate directions. Although significant differences were not detected at the other work rates, there was a trend toward lower range of movement of ASIS at all remaining pedaling/work rate combinations except one. Accordingly, had the sample size been increased, it is possible that the reduced variance of the sampling distribution may have resulted in significance at these remaining combinations. Aside from this possibility, the data conclusively indicated that the patterns of HJC movement indicated by the two methods were fundamentally different in the X-direction (Figure 1a).

To establish the importance of the results showing fundamental differences in HJC movement between ASIS and TRO in magnitude in the Z-direction and phasing in the X-direction, it is necessary to demonstrate that ASIS is a more accurate method to describe HJC movement. Because invasive procedures such as those described in Neptune and

Table 4 Method Comparison of Peak Hip Joint Force Power as a Function of Pedaling Rate and Work Rate (W)

		Work rate					
		150 W		225 W		300 W	
		M	*SD*	*M*	*SD*	*M*	*SD*
60 rpm	ASIS	17.08	3.21	28.99	3.90	47.90‡	14.67
	TRO	27.96	6.26	41.06	8.73	59.89‡	13.09
90 rpm	ASIS	12.42	2.73	18.37	4.68	32.46	9.36
	TRO	29.59	4.92	39.03	11.39	60.69	18.00
120 rpm	ASIS	14.63	5.34	22.67	7.98	40.73	11.59
	TRO	39.05	7.57	59.45	14.91	92.76	9.96

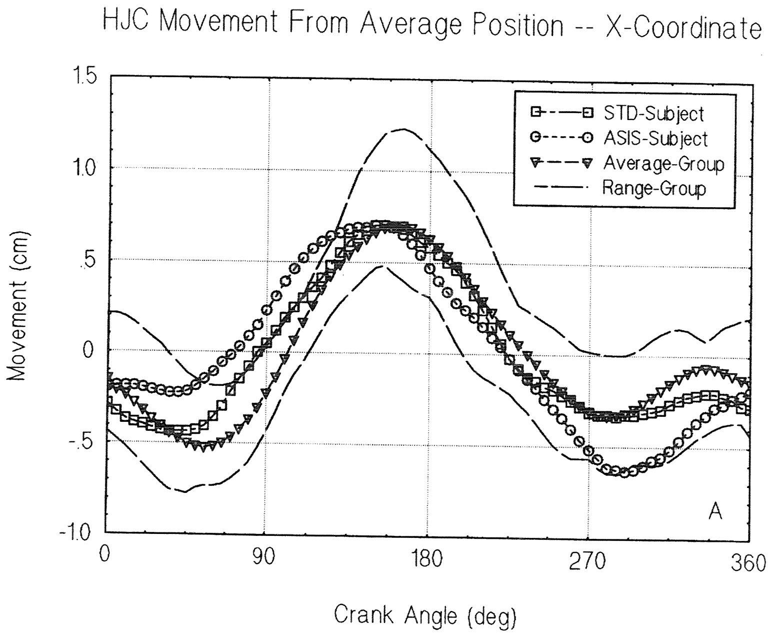
‡No significant difference between ASIS and TRO ($p < .05$). At all other combinations of pedaling rates and work rates, the computed peak hip joint force power was significantly different between methods ($p < .05$).

Table 5 Method Comparison of Hip Joint Force Work as a Function of Pedaling Rate and Work Rate (J)

		Work rate					
		150 W		225 W		300 W	
		M	*SD*	*M*	*SD*	*M*	*SD*
60 rpm	ASIS	6.79	2.16	11.59	2.97	19.87	7.29
	TRO	13.92	3.63	21.55	5.50	31.01	7.31
90 rpm	ASIS	2.32	1.34	4.40	2.12	8.32	4.17
	TRO	6.42	1.56	10.77	1.84	18.91	5.61
120 rpm	ASIS	–0.68‡	1.39	1.39	1.95	4.28	3.35
	TRO	1.33‡	2.47	5.58	2.67	12.30	3.77

‡No significant difference between methods ($p < .05$). At all other combinations of pedaling rates and work rates, the computed hip joint force work was significantly different between methods ($p < .05$).

Hull (1995) were not used to quantify the HJC movement errors, a more circumstantial argument must suffice. This circumstantial argument can be made based on a comparison of the results from Neptune and Hull (1995) with those here. When the patterns of average marker movement for the 7 subjects in this study are compared to those patterns for the single subject in Neptune and Hull (1995), these patterns agree in phase almost identically (Figures 3 and 4) and the movement for the subject of Neptune and Hull (1995) is nearly always within the range of the 7 subjects throughout the crank cycle. The close



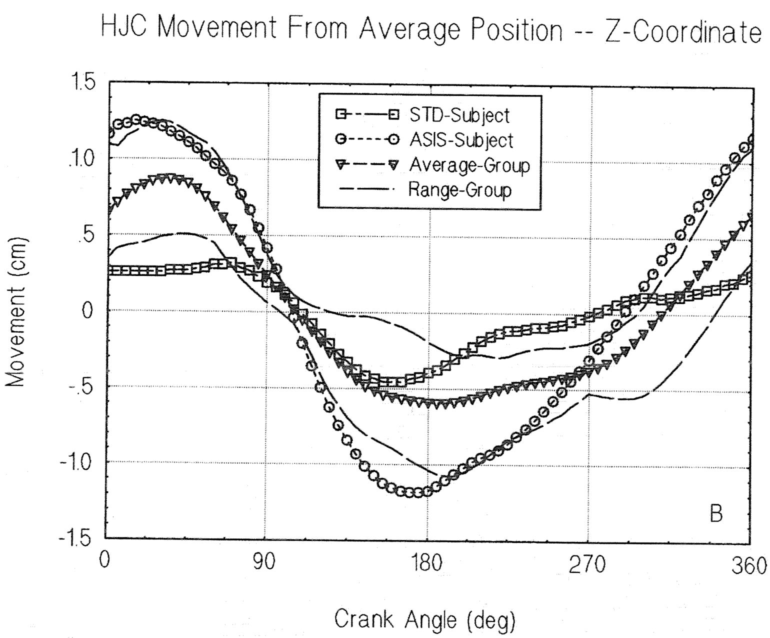
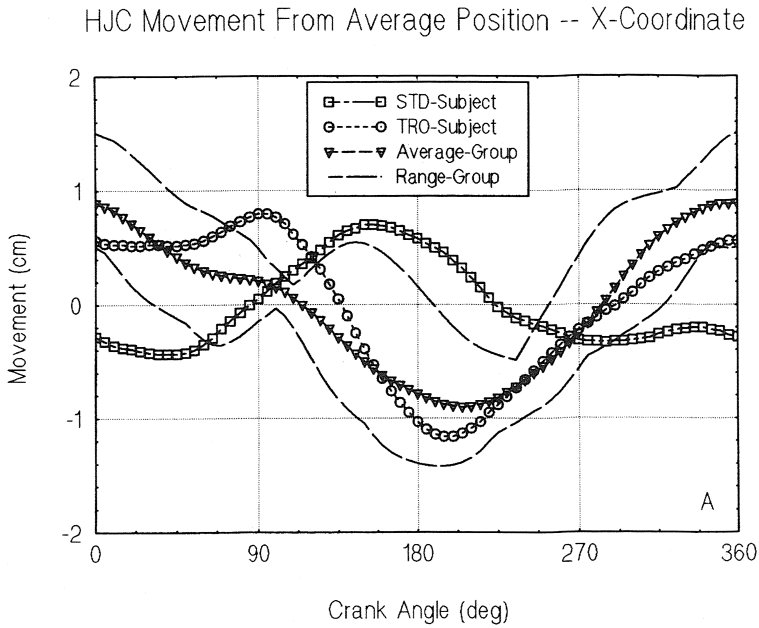


Figure 3 — ASIS method hip joint center (a) X-coordinate and (b) Z-coordinate movement from the average position as a function of crank angle comparison (90 rpm, 225 W).



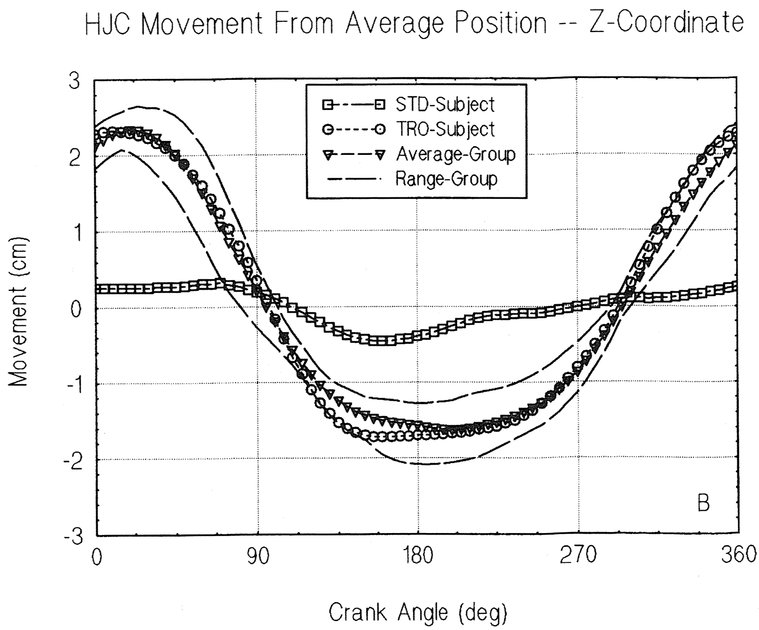


Figure 4 — Trochanter method hip joint center (a) X-coordinate and (b) Z-coordinate movement from the average position as a function of crank angle comparison (90 rpm, 225 W).

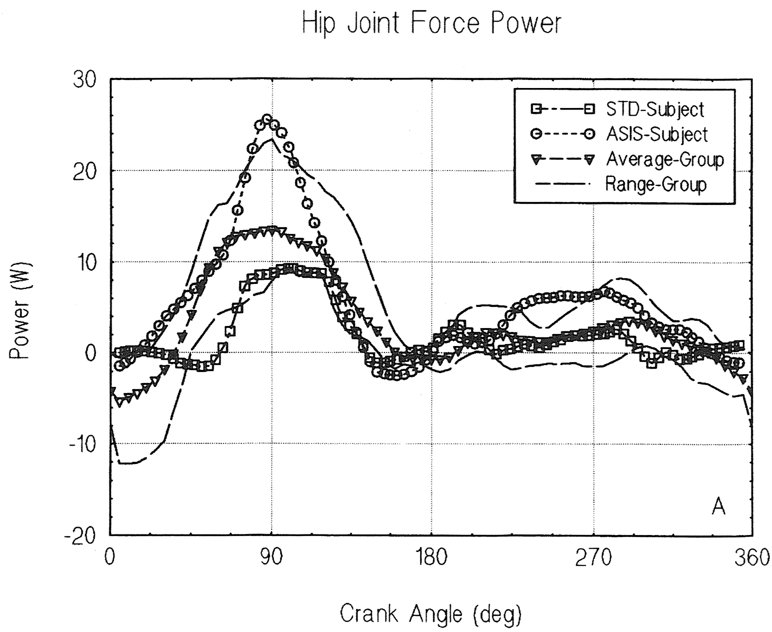
correspondence between the movement patterns of TRO and ASIS for the 7-subject sample and those of the single subject in Neptune and Hull (1995) supports the assumption that the true HJC movement of the single subject is also representative of the sample. Given this assumption and the result that ASIS was shown through direct comparison against a standard method to be more accurate than TRO (Neptune & Hull, 1995), the results of the present study suggest circumstantially that ASIS is generally the more accurate of the two methods.

The extension of this circumstantial argument to the hip joint force power and work leads to similar conclusions about the accuracy of these methods when computing biomechanical quantities. Figure 5 compares the hip joint force power between the 7 subjects of this paper and the subject of Neptune and Hull (1995). Again, the phasing of the two curves is almost identical, with the average ASIS curve of the 7-subject sample more closely matching the STD curve of the single subject than TRO. Although the subject of Neptune and Hull (1995) produced higher peak power, the curve nearly always remained within the range of the group for both ASIS and TRO. Further, a comparison between Neptune and Hull (1995) and Tables 4 and 5 shows that the subject also remained within 2 standard deviations of the average peak hip joint force power and work at all combinations of work rate and pedaling rate of the 7 subjects. These results show that both the values of the work and power calculations are similar between the subject of Neptune and Hull (1995) and the 7-subject group. Moreover, the statistical analysis revealed significant differences between methods at all combinations of work rate and pedaling rate except at the one combination noted. Together, these two results suggest that the ASIS method should be preferred over TRO when computing the hip kinetic quantities of power and work.

Although the movement quantities of the single subject of Neptune and Hull (1995) occasionally deviated from the group range, such deviations are the result of normal variability in the quantities measured. Factors that introduce movement variability between subjects include pedaling mechanics, seat height, anatomical asymmetries (e.g., leg length differences), and differences in soft tissue movement. These factors could easily account for slight phase shift in the pattern of the ASIS X-coordinate movement (Figure 3a) as well as the greater extremes of the ASIS Z-coordinate movement (Figure 3b). Therefore, the deviations do not weaken the assumption that the true HJC movement of the single subject of Neptune and Hull (1995) is representative of the group.

Beyond testing the hypotheses related to the accuracy of ASIS versus TRO, another objective was to evaluate hip movement as a function of both pedaling rate and work rate. The motivation behind this objective was to identify those combinations that gave minimum movement, thus providing some guidance as to those conditions under which FIX would be appropriate. This identification is of value to future studies since the experimental protocol can be simplified by eliminating the acquisition and analysis of hip kinematic data. Further, greater confidence can be placed in the results of past studies that have used FIX under these conditions. This evaluation was made through an analysis of variance polynomial contrast so that the effects of the two independent variables could be separately assessed. Although this analysis was performed with data from both ASIS and TRO, the previous results suggest that ASIS provides the more accurate description of hip joint movement; thus, only the data from ASIS were used in the evaluation.

Based on the results of the polynomial contrast analysis, hip movement was minimized at the lowest power level independent of pedaling rate and at the 90 rpm pedaling rate independent of work rate. Thus, at 90 rpm pedaling rates combined with power outputs of 225 W or less, the fixed hip assumption would introduce minimum error. The one



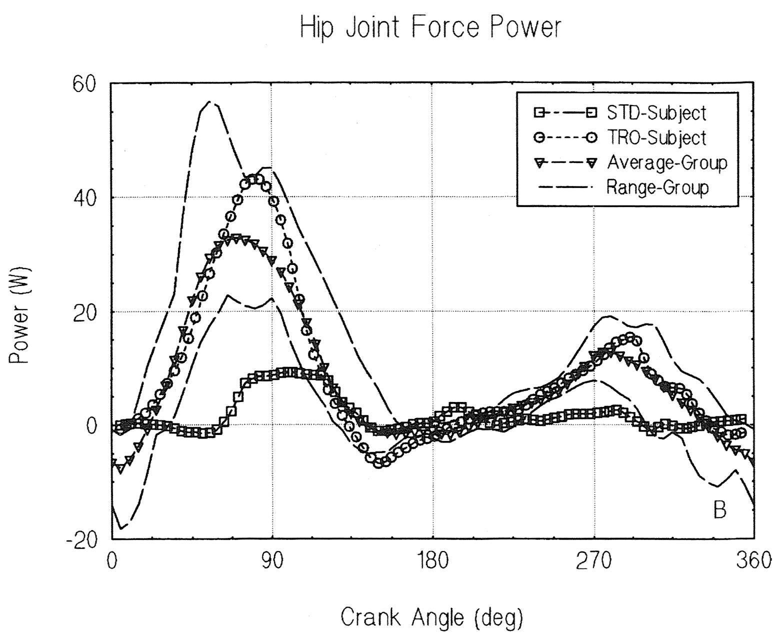


Figure 5 — Hip joint force power (a) ASIS and (b) TRO methods as a function of crank angle comparison (90 rpm, 225 W).

qualification to this conclusion lies in the nature of the population that the subject sample represents. All subjects who participated were competitive cyclists, so that the 225 W work rate was not particularly stressful. Thus, the conclusion pertains to this population. If interest were focused instead on a population for whom this work rate would be stressful, then some downward adjustment in the work rate might be appropriate. Conversely, if interest were focused on elite cyclists, then some upward adjustment may be warranted.

Although some adjustment of the work rate might be appropriate depending on the cyclist population of interest, no adjustment appears appropriate for pedaling rate. A number of studies have shown that approximately 90 rpm is the preferred pedaling rate of trained cyclists (e.g., Hagberg, Mullin, Giese, & Spitznagel, 1981). Moreover, a recent study by Marsh and Martin (1993) showed that noncyclists naturally gravitate to this same pedaling rate.

A final remark concerns the use of FIX. The fixed hip position for each subject was checked between test conditions by analyzing the average HJC coordinates produced by ASIS. Some subjects exhibited measurable changes primarily in the X-coordinate, while others did not. Accordingly, for those subjects who exhibit changes, the HJC coordinates should be determined on a condition-by-condition basis.

Conclusions

The main conclusions of this paper are as follows:

1. TRO had greater HJC movement than ASIS at every combination of pedaling rate and work rate. This increased movement produced by TRO also increased the magnitude of computed hip joint force power and work at every combination of pedaling rate and work rate. A comparison between the subject of Neptune and Hull (1995) and the 7 subjects of this study illustrated similar HJC movement and power curve profiles. This similarity suggests that the conclusion of Neptune and Hull (1995), that ASIS significantly improves the computation of hip joint kinematic and kinetic quantities, may be applied to the general population of cyclists.
2. Using the ASIS method, HJC movement increased linearly with work rate but not with pedaling rate, and HJC movement as a function of pedaling rate was minimum at 90 rpm.
3. Using ASIS as an improved measure of HJC movement, either minimum or nearly minimum values were attained at 90 rpm and 150 W in both coordinate directions, indicating that errors associated with FIX are minimized at low work rates combined with the higher naturally selected pedaling rate.
4. Although both ASIS and FIX methods apparently improve the accuracy of modeling the HJC over TRO, neither method is without error. Further research is needed to develop methods that minimize experimental errors in kinematic measurements of cycling.

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