# A Comparative Kinematic and Biomechanical Analysis of Two Gait Simulators

B. Sue Graves, Ed.D., Associate Professor
Department of Exercise Science and Health Promotion
Florida Atlantic University
2912 College Avenue
Davie, Florida 33314
954-236-1263; fax 954-236-1259
sgraves@fau.edu

And

Paul M. Juris, Ed.D.
President, Kinematix Sports, Inc.
3220 Long Valley Rd.
Charlotte, NC 28270
(704) 846-1014
pjuris@mindspring.com

## *Introduction*

The maturation of the fitness movement has brought with it an increasingly sophisticated consumer that has become concerned with the stress which activities such as jogging or running impose on the body. In order to maintain and improve their level of fitness, many in this group have sought out new modalities that provide the desired training stimulus but with reduced wear and tear. To meet this demand manufacturers first introduced treadmills with impact absorbing suspension systems.

Later, the entire nature of weight-bearing cardiovascular exercise was altered with the introduction of gait simulators. These devices mimic walking and running by keeping the user suspended on two moving foot plates. Unlike treadmills, however, gait simulators impart no jarring forces on the user, by virtue of the fact that the foot never leaves the support platform.

The perception in the fitness marketplace is that these devices are challenging, yet innocuous training modalities, delivering the benefits of moderate to high intensity cardiovascular exercise, without the potential physical risks associated with activities such as running [1,3,4,6]. The problem is that not all joint stresses are created by direct impact loading. Joints may also be exposed to torques which induce compressive and shear stresses. Often, these go largely unnoticed until joint strain arises. Thus, the global perception of a kinder and gentler device may be flawed.

The degree to which a gait simulator induces joint stress is entirely a function of its design. The initial design utilized an elliptical path of motion and was referred to as an elliptical cross trainer. A new class of gait simulator, is designed around an arcuate path of motion, and has thereby been designated an arc trainer.

The purpose of this investigation is to examine the kinematics and biomechanics of these gait simulators and to compare them to normal ambulatory conditions.

## *Methodology*

This study utilized a newly constructed portable force-plate useful in measuring kinetic data from exercise equipment with moving platforms. This force-plate is a sandwich design that utilizes three button type load cells to measure vertical loads and one forward mounted load cell to measure horizontal loads. Crank arm position on the elliptical cross trainer was determined though the use of an optical trigger. Arm position for the arcuate cross trainer was measured by a potentiometer. Knee angles were measured by a goniometer. The output of the load cells, optical trigger, potentiometer and goniometer were fed to a low-noise servo amplifier and then to an analog-to-digital conversion board. The output of the conversion board was sampled at 100 Hz and written to an Excel (Microsoft©) spreadsheet. The system was calibrated using certified weights at 100 lbs. and verified at 25, 50 and 75 lbs.

The subject was healthy, not pregnant and had no orthopedic or musculoskeletal injuries for the past year.

The participant was introduced to both machines in one session. Adhesive reflective markers were placed on the right greater trochanter, knee (center), lateral maleolus, calcaneus and longest toe (anterior portion of shoe).

The elliptical cross trainer was the Precor (Woodinville, WA) EFX model 546. The arcuate cross trainer was the Cybex (Medway, MA) Arc Trainer model 600A.

The first machine was randomly selected. For this evaluation, the subject did the highest incline and a high-normalized resistance. The force plate was placed on the right pedal of the machine prior to data collection and a block of similar dimension and mass was placed on the left pedal.

The subject performed a three-minute warm-up. During the test the subject pedaled at a constant crank velocity and was filmed with a digital video camera. After the collection, the subject cooled down and rested. The second machine was scheduled for another test date within seven days.

## *Discussion*

In normal gait, joint movements combine to produce force vectors which are directed into stationary platforms. The resulting ground reaction force vectors (GRFV) displace the center of gravity over the base of support. In other words, normal gait consists of movement of the center of gravity over a stable base. The relative motion of the base beneath the moving individual is determined entirely by the angular motion about the joints. Thus, as the joints move and the center of gravity displaces, the ground will experience relative motion that is a direct reflection of the system moving above it. Expressed as a phasic relationship, the relative motion between the joints, the center of gravity, and the base of support can be considered "in phase."

Cross trainers, on the other hand, reproduce limb kinematics with minimal displacement of the center of gravity. Essentially, these devices utilize a moving base of support under a relatively stable center of gravity. Conceptually, the difference between normal and simulated gait is very subtle. After all, they both involve relative motion between the center of gravity and the base of support. The issue is whether the movement of the base is consistent with the joint displacement occurring above it, establishing a natural phasic relationship between joints and base, or whether base motion is inconsistent with joint motion, creating an artificial, aphasic condition, which may impose unforeseen stresses on the joint structures. The elliptical cross trainer may, in fact, create the latter condition as explained below.

The elliptical cross trainer functions on what can be described as a "crank and slider" mechanism. In this configuration, a foot plate is attached to a lever arm, which in turn is coupled with a rotating crank at the rear of the machine. On the anterior end of the lever is a wheel which rides along a sloping ramp. Figure 1 below illustrates the crank and slider configuration of the elliptical cross trainer.

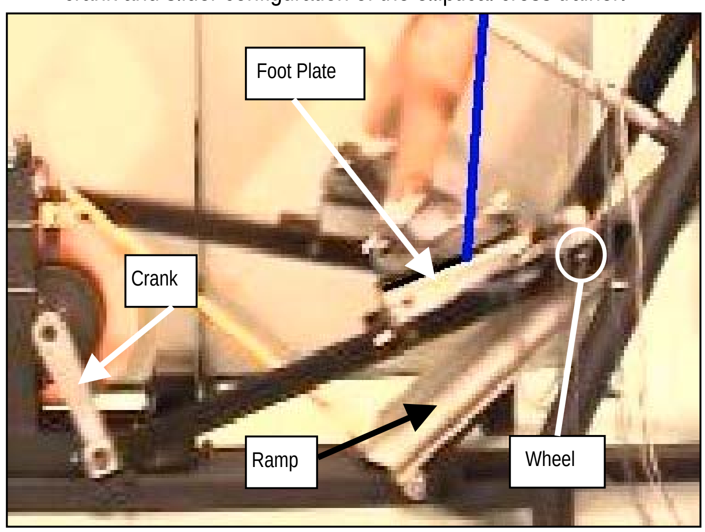


**Figure 1.** Crank and slider mechanism of elliptical cross trainer

A central characteristic of this system is the lever arm and the foot plate are fixed, so that any action of the lever creates the same action at the foot plate. The rotating crank moves the posterior end of the lever arm up and down, causing a change in angle, as well as fore and aft, resulting in linear displacement of the platform. Although linear and angular changes occur in normal gait, the difference here is in the timing of the linear and angular motions, and the phasic relationship between those movements and the movements about the joints. The position of the elliptical cross trainer platform during one step cycle is illustrated in Figures 2, 3, and 4.

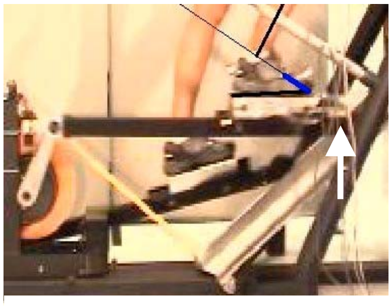

Figure 2. Start of step cycle with right leg.

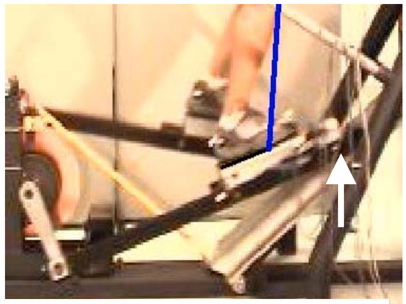

Figure 3. Middle of step cycle.

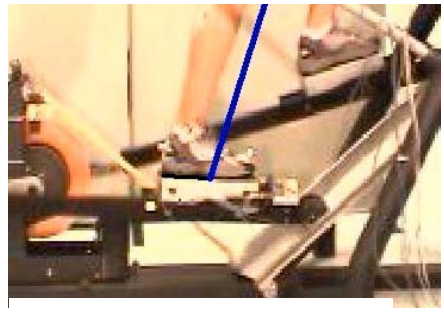

Figure 4. End of step cycle.

At the beginning of the step cycle, Figure 2, the lever and foot plate are parallel to the floor. The white arrow in this figure indicates the position of the wheel on the front of the lever at the top of the ramp. In Figure 3, half way through the step cycle, the foot plate has rotated significantly, but little linear motion has occurred. The white arrow in this frame shows that the wheel has only marginally changed its position on the ramp. By the end of the step cycle, depicted in Figure 4, the lever has slid down the ramp, a result of both linear and angular movements.

Essentially, this pattern is a blend of asynchronous linear and angular movements, and more critically, linear and angular velocities. Consider the velocity profiles in Figure 5. The linear and angular velocities of the foot plate can be seen to be clearly out of phase. At the beginning of the step cycle, the angular velocity of the foot plate is increasing slightly while its linear velocity is decreasing sharply. Moments later, there is virtually no linear change in position while a considerable rate of angular displacement (solid arrow) exists. Nearly half way through the step cycle, the pattern reverses, wherein significant linear velocity occurs while angular velocity slows to zero (dotted arrow). The step cycle ends at the second nadir of the linear velocity curve – notice the high angular velocity at this point – after which the foot plate swings back towards the starting position, completing the stride.

The movement profile has another curious aspect. In normal gait, approximately sixty percent of the stride is spent in the stance phase. The downward phase of this movement, which comprises the stance phase, consumes approximately seventy percent of the total stride time. The additional ten percent of time spent in stance seems to be a function of the design of the mechanism.

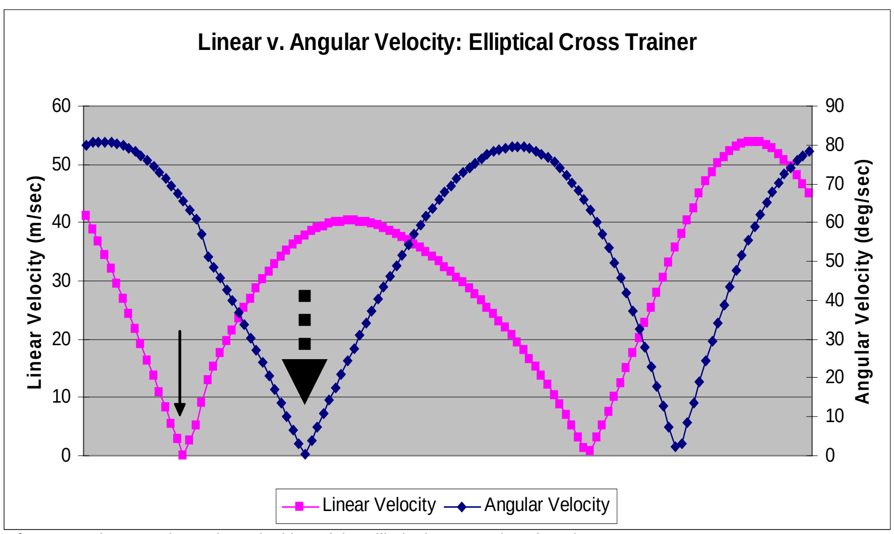


Figure 5. Linear and angular velocities of the elliptical cross trainer footplate.

The initiation of the stance phase is depicted in Figures 6, 7, and 8. The time between each frame is three one-hundredths of a second. The dotted vertical line provides a visual reference against which to gauge the motion of the foot plate. In the first frame, Figure 6, the rotating crank arm is pushing the posterior end of the lever both anteriorly and inferiorly. Even though the limb is set to initiate a downward and posterior motion, the rotation of the crank, pushing the lever against the sloping ramp, actually causes the foot plate to move forward and upward (seen in the Figure 7).

In Figure 8, the crank continues its rotation, now contributing more to the downward movement of the posterior end of the lever, but the anterior end has moved farther forward, rather than backward. Not until the crank arm has exceeded ninety degrees of rotation will downward movement of the foot plate ensue. This delay in the onset of downward movement not only increases the duration of the stance phase, but also results in asynchronous activity between the hip and knee.

Figure 6. Initiation of stance phase, right leg

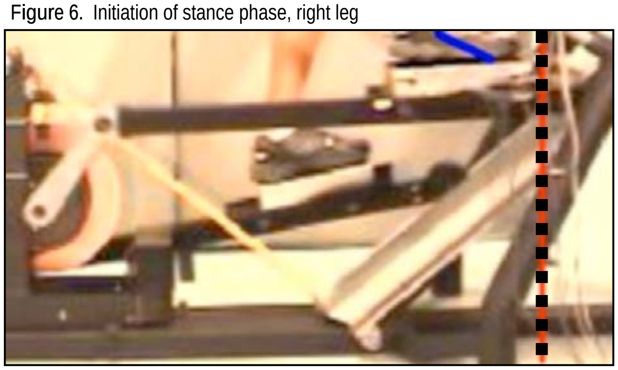

Figure 7. Initiation plus .03 seconds into stance phase.

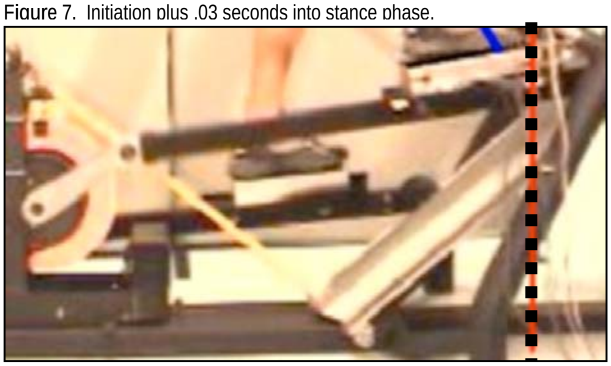

Figure 8. Initiation plus .06 seconds into stance phase.

The two arrows in Figure 9 draw attention to the displacement of the hip and knee joints at the beginning of the downward movement phase. The knee, in this case, has reached peak flexion and begun extension before the hip reaches full flexion. The actual latency between these events is .04 seconds. While apparently small, the timing offset between knee and hip motion is sufficient enough to load the knee, and transfer forces from the hip to the knee, as will be discussed later. Additionally, when noting the kinematics of the hip and knee on the arcuate cross trainer, no such latency will be demonstrated.

The movement of the knee into extension is brought on by the anterior displacement of the foot plate, as discussed above. The continuing flexion of the hip, on the other hand, is not so much a product of the anteriorly moving foot plate as a function of the angular change in the foot plate.

Note, as the hip approaches full flexion, the foot plate is rapidly moving into dorsiflexion, accompanied only by slight anterior translation of the base. That is, while the limb system is coming under load, the motion of the hip and knee has not translated into downward linear motion of the base, but rather an abrupt change in the pitch. This sudden introduction of dorsiflexion into the movement sequence might normally cause posterior loss of equilibrium[2,5]. Since the knee is extending with the forward movement of the platform, and can add little to the maintenance of posture, the only strategy available to cope with the change in the base of support is to lean forward from the trunk, and therefore, increase the degree of flexion at the hip.

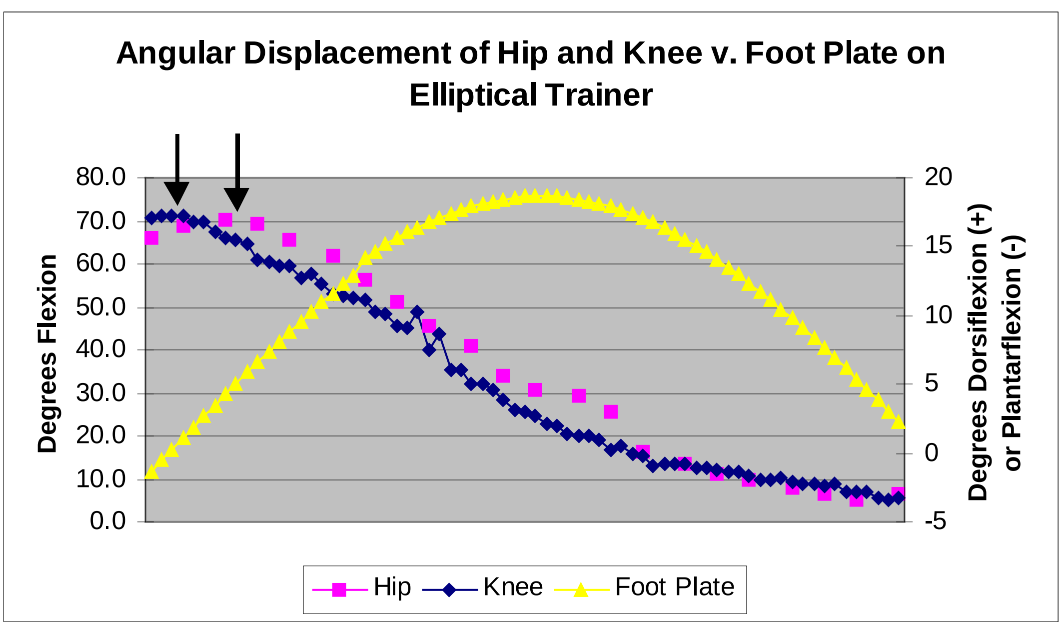


Figure 9. Angular displacement of hip, knee, and foot plate, during initiation of down stroke on elliptical trainer.

The kinematics and kinetics associated with the onset of the step cycle on the elliptical cross trainer illustrated in Figures 10 and 11.

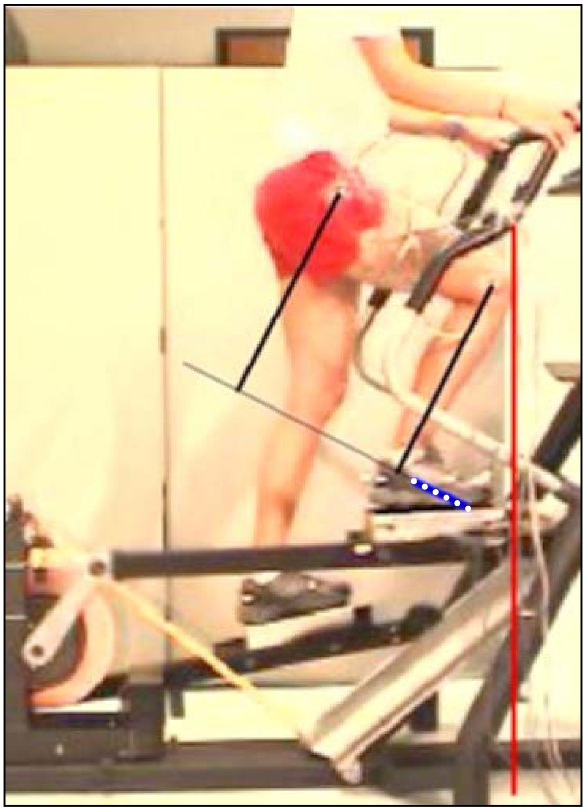

Figure 10. Peak knee flexion.

Figure 11. Peak hip flexion

In these two images, the dotted (blue) line emanating from the foot plate represents the ground reaction force vector (GRFV) for each frame. The lines perpendicular to the extension of the dotted (blue) line represent the external moment arms acting on the respective joints. The total torque is the product of the moment arm and the magnitude of the ground reaction force. In Figure 10, the force is applied mostly anteriorly (horizontally), as the knee initiates extension. The hip, at this time, continues flexing as the trunk is tilted slightly anteriorly. The result is a small GRFV directed mostly posteriorly, and slightly upward. Since the hip is still flexing, the GRFV is generated entirely at the knee. The long moment arm, coupled with a very small force suggests that the knee is generating largely unopposed torques, the result of which is an increase in shear stress at the knee joint.

In Figure 11, however, illustrating peak hip flexion in tandem with the sudden angular change of the foot plate, the GRF direction and magnitude have changed, along with the torque moments about the joints. In this position, the GRFV has become more vertical, and its magnitude has increased. The hip receives an extensor moment, actually facilitating hip extension. The knee, on the other hand, is now working against a significant flexor moment, and therefore becomes the primary motive joint during this phase of the movement. This is compounded by the fact that peak patellofemoral compressive loading, occurring between 75 and 90 degrees of flexion in closed-chain movements[3,8,9] , is combined with increased shear, due largely to the fact that hip motion is unopposed by external forces[9]. The result is significant stress placed upon the knee joint.

Additionally, Siegel and colleagues[7], have demonstrated that extensor moments about the hip may transfer energy to the trunk. Thus, the combination of a slightly flexed trunk with energy transferred from the hip, might serve as a catalyst for hyperactivity of the spine extensors, and potential discomfort in that region.

The movement of the platform of the arcuate trainer is significantly different from the elliptical cross trainer, resulting in kinematics and kinetics which seemingly allow for more synchronous and less stressful motion.

The foot plate of the arcuate path cross trainer, on which the subjects stand, is supported by two parallel arms, which are in turn anchored superiorly to the frame. The arms and the foot plate form a parallelogram which swings forward and aft as the subject moves through the gait cycle. The parallelogram configuration is indicated by the dotted arrow in Figure 12. The motion of the parallelogram is controlled by a crank arm which is connected, anteriorly,

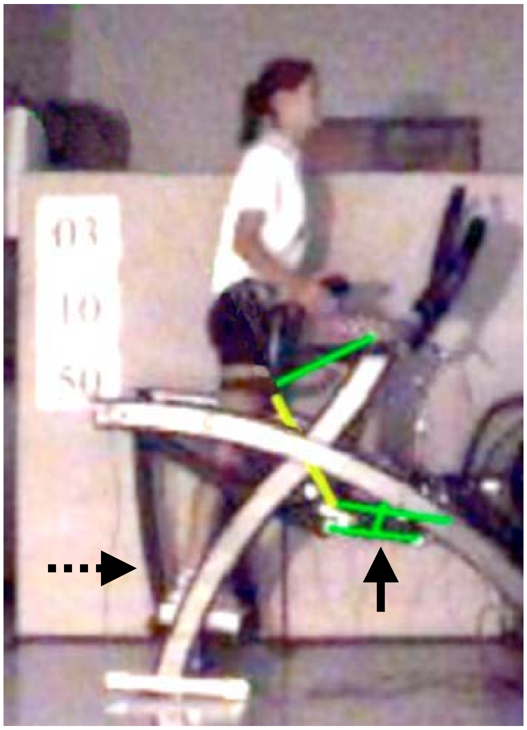

Figure 12. Parallelogram and foot plate of the arcuate cross trainer.

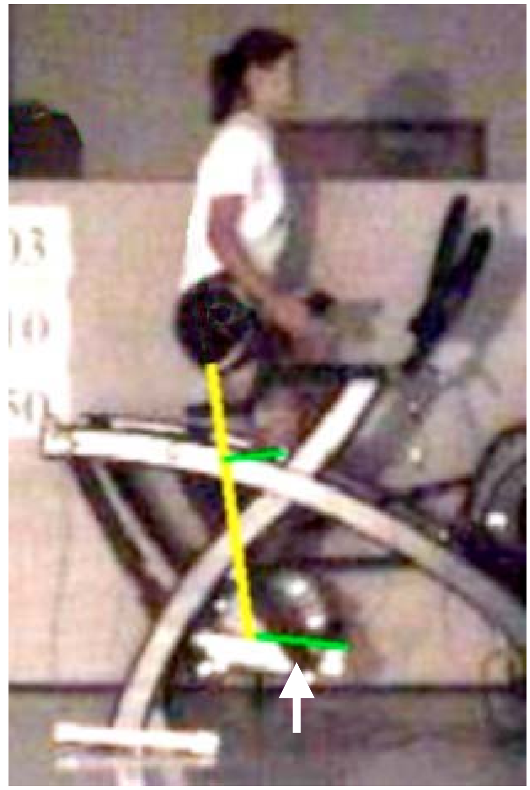

Figure 13. Crank arms of the arcuate cross trainer.

to the drive mechanism of the machine. This can be seen as the horizontal lever, highlighted by the dotted arrow, in Figure 13.

Besides these design differences between the arcuate path cross trainer and elliptical cross trainer, the primary distinction between the two devices is the foot plate on the arcuate path cross trainer maintains a consistent angular orientation in space. Referring again to Figures 12 and 13, the angular orientation of the foot plate at the beginning of the step cycle, indicated by the solid green line and black arrow in Figure 12, is in a slightly plantar flexed position. Half way through the step cycle, in Figure 13, the parallelogram has swung approximately 60 degrees while the foot plate maintains its plantar flexed position (solid white arrow).

Essentially, the support structure (parallelogram) moves angularly while the foot plate moves curvilinearly through space. This configuration basically mimics the movement of one's center of gravity over stair treads, as one might experience while climbing a flight of stairs. The most notable feature of this system is that it moves in concert with the joint and limb motions of the subject.

The angular displacement of the hip, knee, and platform for one stride cycle on the arcuate path cross trainer are depicted in Figure 14. It should be noted, that since the foot plate of the arcuate trainer does not change its angular orientation in space, it has no angular displacement. The "platform", refers to the support arms to which the foot plate is attached. Angular motion in those arms is translated directly into curvilinear motion of the footplate, thus the angular motion of the arms results in synchronous movement of the platform (illustrated in Figure 15). The subject was the same as that for the previous discussion of the elliptical cross trainer.

As illustrated, movement about the joints and platform are precisely in phase. The hip and knee reach peak flexion at the same time the arcuate trainer's platform swings forward to its highest point. As the hip and knee extend, the platform moves in concert towards its lowest position, at which point all three structures return to repeat the cycle. Essentially, movements about the hip and knee are translated instantly into symmetrical movement of the platform.

One can visualize the velocities of the hip, knee, and platform in Figure 14, as the slopes of the displacement curves. Notice the slopes of the knee and hip displacement curves are virtually identical. The angular velocity of the platform is somewhat less than the joint velocities, but this would be expected since the angular displacement of the platform is smaller than the joint displacements. Thus, the rotation of the platform is precisely synchronized to the angular velocities of the hip and knee.

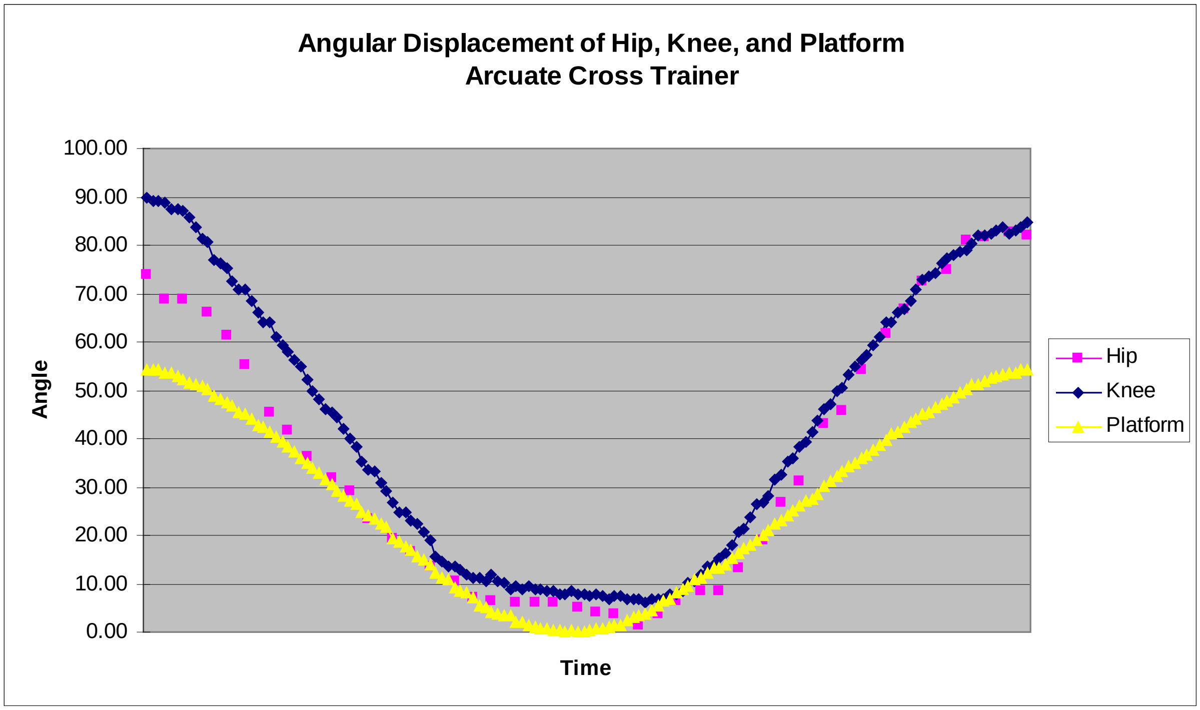


Figure 14. Angular displacement of hip, knee, and support platform on the arcuate path cross trainer.

Stated previously, the foot plate of the arcuate cross trainer has no angular velocity. It does, however, develop linear velocity (actually curvilinear as it moves around a prescribed arc), which is displayed in Figure 15 along with the angular velocity of the platform. As illustrated, the linear velocity of the foot plate is synchronous with the angular velocity of the support arms. The result is moving elements which are not only in phase with each other, but also directly linked to the movements of the subject.

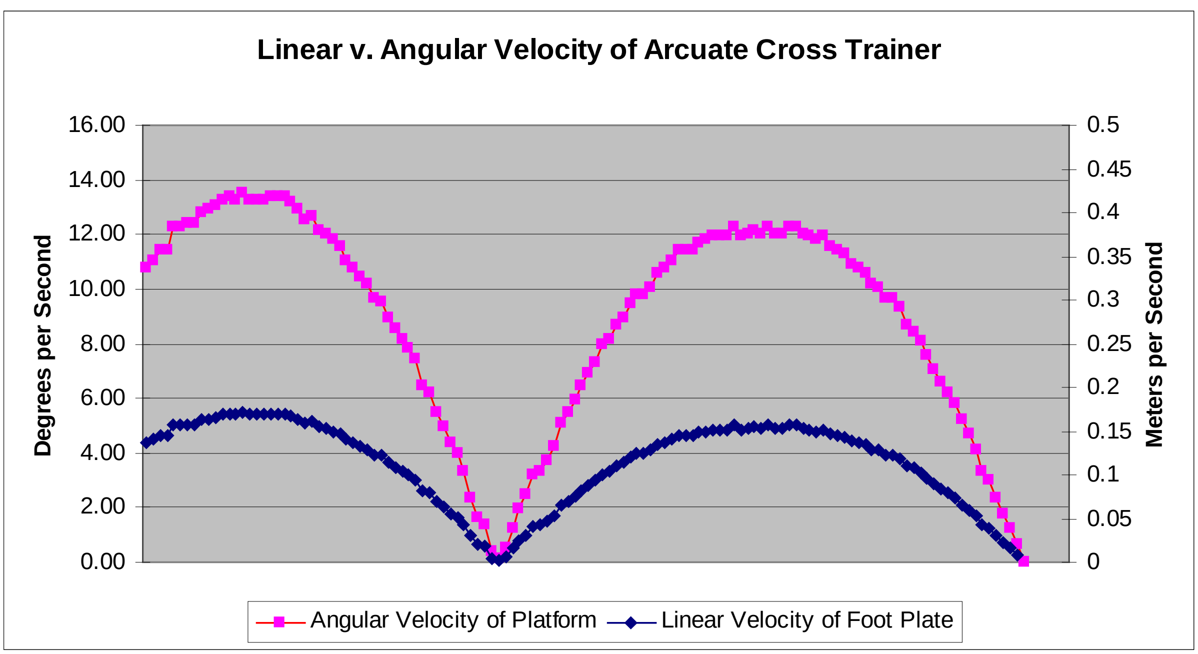


Figure 15. Linear velocity of foot plate v. angular velocity of platform.

Finally, the kinetics at the initiation of the downward phase of motion are displayed in Figure 16. The GRFV is indicated by the yellow line, while the external joint moments are shown as green lines connecting the joint centers to the line extending from the GRFV.

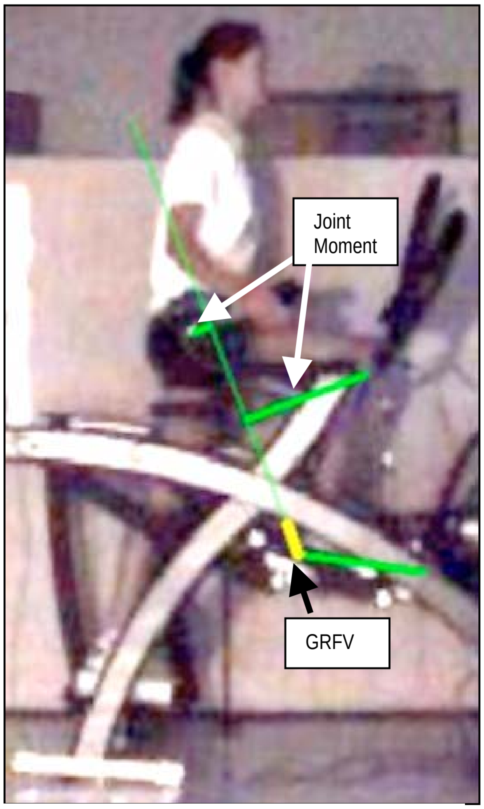


Figure 16. Kinetics of ARC at start of step cycle.

In comparison with the corresponding position on the elliptical cross trainer (Figure 11), the direction of the GRFV is similar, but the magnitude is significantly lower. More importantly, the subject is not compelled to lean forward, as in the corresponding position on the elliptical trainer. The more erect posture is achievable because the hip and knee are not forced into extension by a sudden change in platform angle during the loading phase of the movement. The most significant effect of this upright posture is the hip moment is now acting on the opposite side of the joint, in essence becoming a flexor moment, as opposed to the extensor moment experienced on the elliptical cross trainer.

The hip, now working against flexor forces, contributes more to the downward motion of the platform. The total work is now shared between the hip and knee, as opposed to the elliptical cross trainer in which all work was done at the knee, reducing the force requirement at the knee, and thereby reducing the patellofemoral compression as well. The fact the hip is working against an opposing force, means less unopposed force is transferred to the knee, reducing shear stress at that joint.

The more vertical posture reduces loading on the back, which, in turn, reduces the activation of the spine erectors and thus lowers axial compressive forces within the spine. Clearly, with this cross trainer, the subject and device are tightly coupled, reproducing the kinematics of natural gait, or in this case, natural climbing, in a relatively stress free environment.

## *References*

1. Ballas, MT, Tytko, J, Cookson, D.Common overuse running injuries: diagnosis and management. American Family Physician. 55(7): 2473-2484, 1997.
2. Brown, LA, Jensen, JL, Korff, T, Woollacott, MH. The translating platform paradigm: perturbation displacement waveform alters the postural response. Gait and Posture. 14(3): 256-263, 2001.
3. Cohen, ZA, Roglic, H, Grelsamer, RP et al. Patellofemoral stresses during open and closed kinetic chain exercises. An analysis using computer simulation. American Journal of Sports Medicine. Jul-Aug; 29(4): 480-487, 2001.
4. Dixon, SJ, Collop, AC, Batt, ME. Surface effects on ground reaction forces and lower extremity kinematics in running. Medicine and Science in Sport and Exercise. 32(11): 1919-1926, 2000.
5. Hatzitaki, V, Pavlou, M, Bronstein, AM. The integration of multiple proprioceptive information: effect of ankle tendon vibration on postural responses to platform tilt. Experimental Brain Research. 154(3): 345-354, 2003.
6. Hreljac, A. Impact and overuse injuries in runners. Medicine and Science in Sport and Exercise. 36(5): 845-849, 2004.
7. Siegel, KL, Kepple, TM, Stanhope, SJ. Joint moment control of mechanical energy flow during normal gait. Gait and Posture. Feb: 19(1): 69-75, 2004.
8. Wallace, DA, Salem, GJ, Salinas, R, Powers, CM. Patellofemoral joint kinetics while squatting with and without an external load. Journal of Orthopaedic and Sports Physical Therapy. Apr; 32(4): 141-148, 2002.
9. Wilk, KE, Escamilla, RF, Fleisig, GS et al. A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. American Journal of Sports Medicine. Jul-Aug; 24(4): 518-527, 1996.