



The Cybex Intelligent Suspension System The Science Behind Cybex Treadmills

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Over the last several years, treadmills have fallen out of favor with the fitness public, who instead, has turned to elliptical trainers for their cardiovascular exercise. This, in large part, is due to the noxious effects of repeated impact upon the musculoskeletal system, and the pervasive belief amongst gym goers that non-impact cardiovascular exercise is simply more effective than treadmill running.

Unfortunately, in distancing oneself from treadmills, one also misses an opportunity to experience the benefits that may be derived from running. Researchers have shown, for example, higher bone mineral densities in runners when compared with non-impact athletes (11, 17). Energy expenditure is also significantly higher during running, as compared to either walking or cycling (3, 5).

Running has been linked to increased beta-endorphin levels and mood enhancements (7). It has been associated with increased heart rate and fat oxidation rate, as compared with other forms of aerobic activity (1), and there is some evidence that elliptical trainers induce higher levels of perceived exertion than treadmill running, thus, exercise heart rates may be lower during elliptical exercise as compared to running (2). Lastly, in light of recent findings noting increased knee shearing forces in elliptical trainers with tilting foot plates (10), it is a good time to re-introduce fitness enthusiasts to the benefits and joys of running.

The Cybex Institute conducts extensive research into all facets of human movement. Our goal in treadmill design is to create a running surface that delivers real benefits while, at the same time, limiting the stresses that present risks to the runner. In support of this objective, we evaluated the stresses imposed on the musculoskeletal system at different points during the running cycle, and used that information to formulate a concept for treadmill deck design.

Running gait may be decomposed into two principle phases, one in which the leg is in the air, called swing, and the other during which the leg is on the ground, referred to as stance. All parts of the gait cycle are important, but for the purposes of treadmill design, our focus was on the stance phase, because it is during this period that the stresses of running are imposed on the body.

Although epidemiological research into repetitive use injuries in runners has identified several areas of complaint, it seems that the most common injury site is the knee (4, 18, 19). Thus, our research has initially focused on the kinematics of the knee and the critical biomechanical events that affect it during stance in treadmill running. The results of our investigations explain why we created the IS3 (Intelligent Suspension generation 3)TM treadmill deck.

Identifying Key Stress Points

Figure 1, below, displays three images of a person running on a treadmill at eight miles per hour. In the image at left, the heel is just making contact with the treadmill deck. This is initial contact. In the center image, the foot has moved under the runner's hip, and the center of gravity is positioned over the instep of the foot. This is mid stance. Lastly, at the far right, the foot is pushing off of the treadmill deck at the point of toe off.



Figure 1. Stance Phase of Running

Notice the time sequence of this person running at eight miles per hour. The entire stance phase lasts a mere .234 seconds, that's less than one-quarter of a second. Further delineation of the stance phase reveals that the latency between initial contact and mid stance is less than one-tenth of a second (.083 s), while the time between mid stance and toe off is .151 seconds. These temporal variables are important when considering the actions of the joints and the stresses placed upon them.

We can begin by evaluating the angular displacement of the knee, for one subject, during stance. As a basis of comparison, we'll also examine the hip for the same time interval. These are displayed at right in figure 2. The vertical line indicates mid stance.

As seen in the figure, there is a bimodality between the hip and knee during the stance phase. From the moment of initial contact until just after mid stance, the knee engages in continual flexion from approximately 15 degrees to almost 45 degrees. In contrast, the hip experiences virtually no angular displacement, shifting between 21 and 20 degrees of flexion for the same period. Thus, the knee and hip move independently through the early stance phase. Just after mid stance, however, both joints extend synchronously until the moment of toe off.

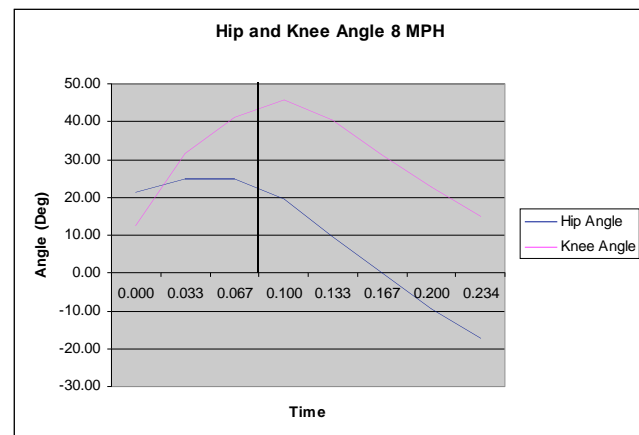


Figure 2. Hip and Knee Kinematic Data

Since the period from initial contact to mid stance involves the transfer of weight and the downward acceleration of the center of gravity onto the lead leg, this can be considered a force absorption phase. Once the center of gravity is positioned over the stance foot, and both hip and knee transition into coordinated extension, the runner has now moved into a propulsion phase.

Now, consider again the duration of the absorption phase; .083 s. With the knee flexing through a range of motion of 30 degrees, its average angular velocity during this phase is -351.42 degrees per second. By comparison, the mean velocity of the hip over this same interval is 12 degrees per second. Examining the knee independently, we can see its displacement and velocity profiles in figure 3. Note again, that the vertical line represents mid stance. Negative velocities indicate that the joint is flexing, while positive velocities denote extension.

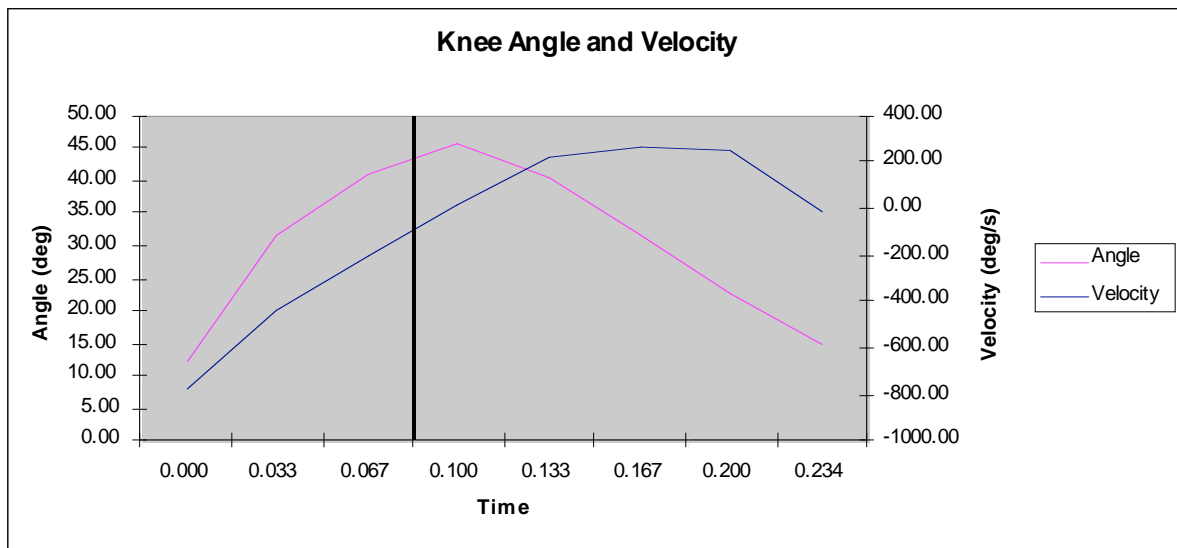


Figure 3. Knee Angular Displacement and Velocity

The angular velocity of the knee, measured on the right side of the figure, is nearly -800 degrees per second at the initiation of stance, and slows to 0 degrees per second just after mid stance, when the knee converts from flexion into extension. In this force absorption phase, the knee's velocity decreases nearly 700 deg/s in .083 seconds, for an average rate of deceleration of 8434 deg/s^2 .

Interestingly, our data reveal that the duration of the absorption phase remains consistent throughout treadmill speeds from 6.0 to 11.0 miles per hour. One might have expected an inverse relationship between belt speed and time to mid stance, with time decreasing as belt speed increases.

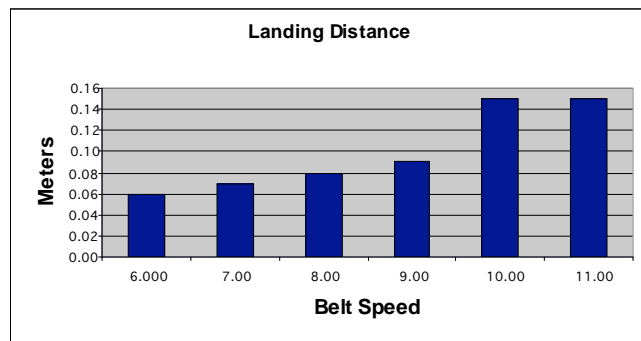


Figure 4. Landing Distance at Different Belt Speeds

According to the data in figure 4, however, runners impart subtle increases in landing distance – the horizontal distance from the heel at initial contact to the vertical projection of the center of gravity – between six and nine miles per hour. The result is to increase stride length in compensation for the faster belt, thereby normalizing force absorption time.

At ten and eleven miles per hour, there is an apparently larger shift in landing distance which accounts for the consistent force absorption times. This marked increase in stride may indicate that the subject had exceeded his running efficiency at those speeds. This, however, is reserved for a different analysis.

From mid stance, the knee accelerates into extension, along with the hip, and reaches a relatively constant velocity until toe off. The mean velocity over this period is approximately 200 degrees per second, considerably slower than the joint's velocity in early stance. It is a reasonable conclusion, therefore, that as a result of a significantly high rate of eccentrically controlled angular deceleration within the first tenth of a second of the stance phase, the knee may be exposed to the greatest amount of stress during this interval. This conclusion is further supported by other concurrent biomechanical and kinematic events.

Forces Generated During Stance

The forces incurred while running have been fairly well documented (9, 20, 21, 22). Figure 5 depicts a typical profile of ground reaction forces as a percentage of body weight, throughout the stance phase of the gait cycle.

In general, ground reaction forces begin to rise at a steady rate from initial contact, reaching approximately 200% of body weight, nearly half way through stance. The

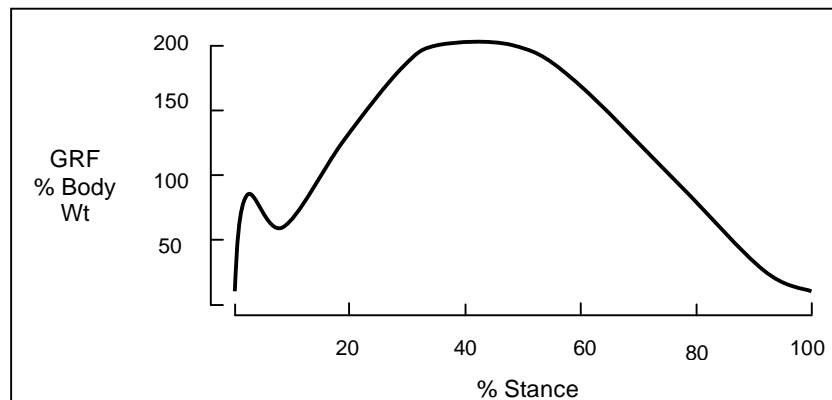


Figure 5. Vertical Ground Reaction Forces During Stance

increased force is a product of the body accelerating towards the ground, and the center of gravity moving over the stance foot. Keep in mind that the knee begins flexing at the moment of initial contact, and continues until just past mid stance, thus enabling the downward movement of the center of gravity. In fact, the ground reaction force profile seen here reaches its peak at roughly the moment that mid stance is achieved and the knee has stopped flexing, followed shortly thereafter by coordinated hip and knee extension for propulsive purposes.

Certainly, ground reaction forces which are twice body weight create significant torque loading at the joints, more specifically the knee. The hip, at mid stance, is in line with the ground reaction force vector, and thus is exposed to relatively small moments of torque. The knee, on the other hand, because of its flexed position, creates a larger moment arm, and is therefore generating more torque prior to accelerating into the propulsive phase of stance.

From another perspective, the increase in loading at the knee, while arguably significant, is also fairly gradual. From figure 5 it can be seen that the increase in ground reaction force, after the initial impulse, begins at approximately 10% of the stance phase, and terminates at 35% of stance. Load, therefore, increases from roughly 60% of body weight to 200% of body weight over 25% of the stance phase. In other words, for each percent change in stance, there is a 5.6% increase in load.

Compare this to the portion of the force curve seen at the far left of the figure. Here the ground reaction force curve rises from 0% of body weight to 80% over approximately the first 2% of the stance phase. This means that for each percentage change in stance, there is a concomitant 40% increase in loading, a rate of loading nearly six times as great as any other point of the stance phase.

The cause of this sudden impulse in the force profile is the impact that occurs between the foot and the running surface at the instant of initial contact. According to Watkins (20), this sudden collision between the two structures causes a shock wave which propagates along the mechanical system, especially through the chondral structures of the knee (8, 15).

Peak impact force occurs at approximately 2 ms into the stance phase, a point at which the knee is flexed to less than 25 degrees. Thus, the knee is in a position of relative extension when impact forces act upon it, and may be more susceptible to strain.

A Treadmill Solution

Clearly, the body is placed under a significant amount of stress during running, with potential detrimental effects emerging from long periods of exposure. Thus, the benefits from running that were discussed earlier may be inconsequential should repetitive use injuries occur.

Treadmills, on the other hand, may provide an opportunity to effectively reduce the stresses placed on the structures, while at the same time imposing substantive metabolic demands. An obvious solution is to manufacture a more forgiving treadmill by introducing a flexible deck. It's not difficult to imagine that a surface which gives will certainly help to mitigate mechanical stresses.

We cannot assume, however, that the mere introduction of a flexible surface will solve running problems on treadmills. First we must understand how a softening of the running surface influences the kinetics and kinematics of running, if at all.

The first question is whether a soft running surface attenuates the forces experienced during running. There are no studies which examine ground reaction forces on treadmills with differing deck stiffnesses. This is a practical matter. Ground reaction forces are measured on force plates, which are, by their very nature, rigid structures. In creating an instrumented treadmill, therefore, one would effectively remove any flexibility from the deck. On the other hand, one can place objects of varying stiffness on a force plate, and measure the ground reaction forces applied through those objects.

For example, Salem et al (16) examined the forces associated with stepping and jumping on exercise step benches with different degrees of stiffness. Their question was whether stepping and jumping on three benches with different hardnesses, would produce different magnitudes of ground reaction force. They discovered that despite the fact that the benches had significantly different degrees of forgiveness, the magnitude of the ground reaction forces was identical for each condition. In other words, flexibility of the surface did not reduce the level of force loading on the performers.

What Salem and colleagues did discover, however, is a direct relationship between the softness of the support surface and the rate of force application. Their data revealed that as the stiffness in the support surface decreased, the rate of rise of the ground reaction forces also decreased. These findings are corroborated by Nigg, Denoth, and Neukomm (12).

Nigg, et al, instead of examining step hardness, observed the force profiles of running shoes with varying sole hardnesses. This is another means by which one can evaluate support surfaces while running. Like Salem et al, Nigg and colleagues discovered that soft soled running shoes did not reduce the absolute magnitude of the ground reaction forces, but they did attenuate the impact forces that occur at initial contact.

The results of these studies suggest that no matter what one does in the manner of treadmill deck design, ground reaction forces cannot be reduced. On the other hand, carefully positioned flexibility in the deck may limit shock. The question then, is which part of the deck should give? To address this, we need to look at how flexible surfaces affect joint kinematics.

Rear Foot Motion and Running Surfaces

To fully understand the impact of flexible surfaces on the function of the lower extremity, it is necessary to examine the kinematics of the rear foot, tibia, and knee during the stance phase of running.

As weight is transferred onto the lead leg during stance, the center of gravity shifts laterally over the single base of support. The lateral displacement of the center of gravity is accompanied by adduction of the stance hip, and eversion, or pronation, of the subtalar joint, or rear foot (14, 23). These joint kinematics assist in establishing a balanced position and in absorbing some of the forces of impact.

Additionally, there is a concomitant internal rotation of the tibia in association with rear foot eversion. Tibial rotation is also driven by knee flexion and extension, thus, as the knee flexes during stance, the tibia internally rotates, and as the knee extends, the tibia externally rotates. These are further coordinated with subtalar motion.

In figure 6, at right, we can see the relative motion of the rear foot (red) and the knee (dotted) joints during stance. When the foot makes contact with the ground, the subtalar joint is slightly inverted, but then goes through rapid eversion through the first 10% of the stance phase. This is accompanied by rapid flexion at the knee and internal rotation of the tibia.

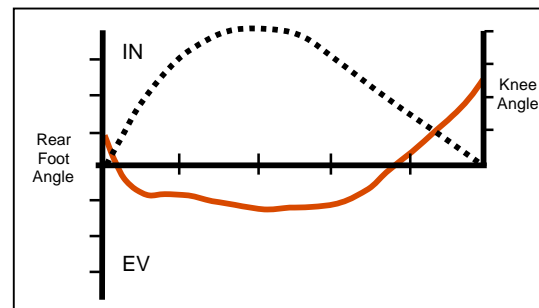


Figure 6. Rear Foot & Knee Motion

Prior to mid stance, the rear foot stops everting, and remains in a fixed position of approximately 5 degrees of eversion, until just after the knee enters extension. At that point the subtalar joint supinates to a neutral position, and then ultimately into inversion as the foot pushes off the ground. This subtalar motion is accompanied by external tibial rotation, creating a neutral and balanced position at the knee joint. This is the normal interaction of the knee, tibia, and subtalar joint (6). What then, are the effects of soft running surfaces on these mechanical actions?

Hamill and colleagues (6) addressed this question by examining rear foot, knee and tibial motion in runners wearing running shoes with varying mid sole durometers. The effect of shoe stiffness is to create a firmer or more forgiving support surface beneath the foot, especially at mid stance.

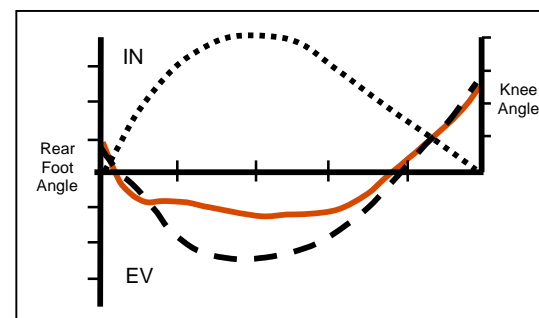


Figure 7. Effects of Soft Surface on Rear Foot Motion. Red line is normal motion, dashed line is motion due to soft shoe midsoles.

A composite of their findings is illustrated in figure 7, at right. The figure shows the normal movements of the knee and rear foot under firm support conditions, as depicted in figure 6. In addition, the dashed line displays rear foot motion when runners wore a shoe with a soft midsole.

It is evident, in figure 7, that during the first ten percent of the stance phase, rear foot motion in the soft shoe reflected the motion occurring under the firm condition. So, shoe softness did not inhibit normal rear foot motion early in stance.

The movement profiles deviated, however, from that point forward. Whereas under firm conditions the rear foot stopped evertting, the softer condition allowed the rear foot to completely evert to the physical limitation of the joint. This also affected the tibia, which continued to rotate internally. Subsequently, the timing between knee extension, rear foot supination, and tibial external rotation was disturbed, so that the knee accelerated into extension against an internally rotated tibia, placing stress on the tibio-femoral and patello-femoral joints. The authors suggest that disruption of the timing between the subtalar joint, tibia, and knee due to soft running surfaces may be a potential mechanism for knee injury.

Treadmill decks, admittedly, don't share all the characteristics of running shoes. Whereas running shoe mid soles may distort in both the sagittal and frontal planes, treadmill decks flex longitudinally, thus the ensuing motion of the rear foot may not be equal under softened shoe and treadmill conditions. In fact, one could argue that the deck doesn't at all affect the extent of subtalar or tibial motion during the absorptive phase. On the other hand, there is evidence that the softness of the surface may have a significant influence on the rate, timing, and precision of foot and tibial motion as the runner transitions into propulsion.

We have learned that while soft support surfaces do not reduce the magnitude of ground reaction forces, they do limit the rate of force application, causing a delay in the return of those forces (12, 16). The movement of the foot, in this case, is highly dependent upon the ground reaction forces. The foot won't begin to supinate until the forces it creates are returned from the support surface. If those forces are delayed, then the ensuing foot motion will also be delayed, as will the external rotation of the tibia.

Consequently, even if the range of subtalar and tibial motion is normal on a mid-flexing treadmill deck, their timing, relative to extension at the knee, will be disturbed. The knee will accelerate into extension against an internally rotated tibia, placing unnecessary stress on the tibio-femoral and patello-femoral joints, with potential repercussions for the runner (9).

Thus, the simple fact that a treadmill flexes may not prove to be both effective and safe. The position and length of the flexing section of the deck must be carefully considered in order to create the best possible solution.

The Cybex Treadmill Solution

As a result of the research conducted by the Cybex Institute, we have gathered critical information regarding the biomechanics of running and the impact on treadmill design.

We have discovered that the greatest stressors during running are the impact and shock that arise within the first few milliseconds of stance, as the knee is initiating high velocity, eccentrically controlled flexion. Also during this time, the subtalar joint is undergoing rapid eversion, and the tibia is internally rotating.

The literature also suggests that while ground reaction force magnitudes may not be reduced, the initial shock may be attenuated by introducing a forgiving running surface. By placing the flex point at the front of the deck, not only will shock be suppressed, but the normal kinematics of the knee, tibia, and rear foot will be preserved.

Once the structures of the leg have stabilized, the deck should be firm, allowing for the proper return of the subtalar joint to a neutral and then inverted state, the correct external rotation of the tibia, and appropriate acceleration of the hip and knee.

The Cybex IS3 treadmill design embodies all of these characteristics. The patented front end has suitable cushioning, minimizing shock on the joints, while the mid and aft sections are firm enough to encourage proper joint kinematics. Runners will experience a superior running surface, delivering maximal benefits with minimal stress, helping to ensure outstanding results.

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