KINEMATICS OF ELLIPTICAL AND TREADMILL EXERCISE
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ABSTRACT

This study compared the kinematics of two kinds of elliptical training to treadmill jogging. Video analysis was performed during exercise on the three machines at different paces. Image processing techniques were employed in Matlab to identify the trajectories of an ankle, knee, and hip marker, which were used to calculate the knee flexion angle and to estimate stride characteristics. The one degree-of-freedom (1-DOF) elliptical stride was 0.464 ±0.005m, around 60% of the maximum jogging stride length (0.768 ±0.136 m) and did not vary significantly with speed (p<0.05). This elliptical created smaller knee flexion angles than jogging. The 2-DOF elliptical exhibited maximum stride lengths of 0.551 ±0.017 m, around 70% of the maximum jogging stride, which varied significantly with pace (p<0.05). This elliptical also exhibited stride heights more than 150% that of jogging and large prolonged knee flexion angles that did not vary with pace. This was attributed to a kinematic singularity in the mechanism design. Further studies should measure forces to determine if this results in increased loading of the knee joint.

1. INTRODUCTION

Elliptical training is a low impact form of aerobic exercise that is often incorporated into exercise regimes for those rehabilitating from surgery or suffering from chronic overuse injuries. In injured athletes, it is often used as an exercise to help transition to walking and jogging. Most elliptical trainers use a four-bar or five-bar linkage with a single degree of freedom (1-DOF) that guides a person’s foot through a fixed elliptical path. Consequently, the kinematic constraint at the foot in conventional elliptical trainers may significantly alter the ankle, knee, and hip kinematics in undesirable ways. In addition, the added constraint may reduce the natural stride-to-stride variability, which has been shown to play an important role in motor learning and recovery.

Recently, Precor began selling a novel elliptical trainer, the Adaptive Motion Trainer (AMT), which uses a seven-bar linkage with two degrees of freedom (2-DOF) to give the user more control over his or her motion. This may allow a more natural jogging stride without the disadvantage of high impact forces. The purpose of this study was to compare the stride characteristics, stride-to-stride variability, and knee flexion angle over a range of speeds during use of the AMT 2-DOF elliptical trainer, during use of a traditional 1-DOF elliptical trainer (Precor EFX 556i), and during treadmill jogging. It was hypothesized that the AMT 2-DOF elliptical would exhibit stride characteristics that would be more similar to jogging, that would vary with speed, and that would have a stride-to-stride variability similar to jogging. It was hypothesized that the EFX 1-DOF elliptical would exhibit stride characteristics very different from jogging, which would not vary from stride to stride or with a change in speed.

2. KINEMATICS IN ELLIPTICAL EXERCISE

2.1 COMPARISON OF ELLIPTICAL DESIGNS

Most traditional elliptical trainers use a four-bar or constrained five-bar linkage with a single degree-of-freedom (1-DOF) that restricts the foot along a pre-determined, fixed elliptical path. One link of the mechanism is attached to a flywheel, which can have a large resistance and inertia. Figure 1 shows a photograph and a schematic diagram of the kinematic design of the Precor EFX 556i, which was the 1-DOF elliptical used in this study. This elliptical employs a five-bar linkage that
Figure 1: A photograph and schematic diagram of the Precor EFX 556i, the one degree-of-freedom (1-DOF) elliptical trainer used in this study. The 5-bar linkage mechanism results in a constrained elliptical path at the foot. The tilted line represents the fifth imaginary link, which connects the fixed points at the flywheel and the machine base.

is constrained to 1-DOF by a tilted slider attached to the end of the link that supports the pedal. This should result in an elliptical path of the foot, as shown in the diagram.

Figure 2: A photograph and schematic diagram of the Precor AMT 2 DOF elliptical trainer used in this study. The mechanism consists of a main link, which can pivot about a point fixed to the elliptical base, whose rotation $\phi_1$ is coupled to the rotation of the flywheel. A four-bar mechanism attached to this main link adds an additional degree of freedom to the mechanism, shown in the diagram as $\phi_2$.

2.2 GAIT KINEMATICS

The use of videography to analyze kinematic gait characteristics dates back to the late 1800s, when Eadweard Muybridge used photographs taken in rapid succession to analyze the gait patterns of horses. Advancements in video capturing and processing technologies have allowed for much more complex gait analysis in humans. However, the underlying principle remains essentially the same: still images taken in rapid succession are used to track the movement of limbs for subsequent kinematic analysis of gait. This kind of videographic kinematic gait analysis can provide invaluable insight for clinicians and researchers concerned with sports injury, motor rehabilitation, and age or disease-related gait pathology.

When analyzing kinematic gait characteristics in humans, limb segments can be modeled as rigid bodies. Each limb segment can be assigned a local Cartesian coordinate system that describes the bone shape based on anatomical landmarks. At the intersection of two limb segments, each joint can also be assigned a generalized coordinate system whose axes are chosen for convenience to be one of the fixed anatomical axes of the Cartesian coordinate system describing each limb segment and their mutual perpendicular.

Figure 3 shows the fixed anatomical Cartesian coordinate systems that describe the femur and the tibia, which are connected at the knee joint. The mechanical axis is defined along the long axis of each bone.

The knee joint, which is the focus of this kinematic analysis, can be modeled as a four-link kinematic chain consisting of four single-axis revolute joints. The first and last links in the kinematic chain are the tibia and femur, while the two internal links are imaginary. Figure 3 also provides a visual representation of this simplified model. This model gives us an abstraction of three clinical joint angles: the knee flexion-extension angle, shown in the figure as $\theta_1$, the knee adduction-abduction angle, shown in the figure as $\theta_2$, and the knee internal-external rotation angle, shown in the figure as $\theta_3$. In practice, the clinical knee flexion angle, $\theta_1$, is thus defined as

$$\sin(\theta_1) = -(\mathbf{k} \times \mathbf{l}) \cdot \mathbf{K},$$

where $\mathbf{k}$ is the unit vector pointing along the mechanical axis of the tibia, $\mathbf{l}$ is the unit vector pointing rightward and perpendicular to the mechanical axis of the femur, and $\mathbf{K}$ is the unit vector pointing along the mechanical axis of the femur. Under the simplified assumption that
angles and moments reflect gait pathologies and clinically relevant subtleties, a common way to analyze gait is by dividing it into strides and normalizing by percentage of the stride to compare across strides. In walking and jogging, each stride consists of a stance phase, starting with heel strike and ending with toe-off, and a swing phase, during which the leg is not in contact with the ground. For comparison to walking and jogging in elliptical analysis, the stride is divided into a similar stance phase, in which the leg starts at its most anterior position and swings backward to its most posterior position, and a swing phase, in which the leg starts at its most posterior position and swings forward to its most anterior position. The solid vertical line in Figure 5 represents the transition between stance and swing for elliptical training while the dashed vertical line represents the transition between stance and swing for treadmill walking.

In addition to altering the clinically significant joint angles, the added kinematic constraint imposed by a traditional elliptical trainer is hypothesized to reduce stride-to-stride variability. Natural stride variability may play an important role in neural acquisition of motor skills as evidenced by recent studies with robotic rehabilitation of stroke patients. Most recently, a major study of gait rehabilitation for stroke patients found that manual kinematic training of the stroke patients’ limbs did not significantly increase their improvement in functional mobility. This finding suggests that rehabilitation training using purely kinematic constraints of the limbs may not yield significant long-term motor improvements. Moreover, the repetitive nature of traditional elliptical trainers can be disengaging, and can even deter people from using them even if they need a low impact form of exercise.

Equation 3 is advantageous because it only requires two-dimensional sagittal plane kinematic data.

Previous studies have analyzed the three dimensional kinematic and kinetic gait characteristics in elliptical training and treadmill walking. Because elliptical exercise is low-impact, it is commonly utilized in exercise regimes for people undergoing rehabilitation after knee or hip surgery or for those who suffer from patellofemoral pain syndrome. However, the kinematic constraint that elliptical trainers impose at the ankle alters gait kinematics in a way that may not be desirable for the injured or rehabilitating. One study found that the knee flexion angle and knee flexion moment were increased in elliptical training compared to treadmill walking, shown in Figure 5. Because the time-changing pattern of joint

The tibia is not rotating in the interior-exterior direction, x and X point in the same direction, which means

\[ i = \mathbf{I} \]

which further simplifies the definition of the knee flexion angle to

\[ \sin(\theta_1) = -\mathbf{j} \cdot \mathbf{K}. \]

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![Figure 3: On the left: a pictorial representation of the anatomical coordinate frames of the tibia and femur. The lowercase letters x, y, z describe the tibial coordinate axes with unit vectors i, j, k, while the uppercase letters X, Y, Z describe the femoral coordinate axes with unit vectors I, J, K. The mechanical axis of the tibia is represented by the lowercase z direction, and the mechanical axis of the femur is represented by the uppercase Z direction. On the right: a visual representation of the four-link open chain kinematic model of the knee joint. The kinematic chain consists of three single-axis revolute joints, θ1, θ2, θ3, which correspond to knee flexion-extension, adduction-abduction, and internal-external rotation respectively. Of interest in the remainder of this study is the knee flexion angle, θ1.](image)

![Figure 4: Ensemble averages of knee flexion-extension angle (left) and body weight normalized knee flexion-extension moment (right), both normalized by stride duration. In this study, the solid curve represents elliptical training while the dashed curve represents treadmill walking. The vertical line separates stance and swing phase.](image)
Recently, Precor designed a new commercially available elliptical trainer, which they call the Adaptive Motion Trainer (AMT). This unconventional elliptical trainer gives two degrees of freedom instead of one, allowing for a continuously adaptable stride within the machine’s mechanical limits. This new machine may offer a form of low-impact exercise that does not limit natural stride motion and variability. The goal of this study is to compare the stride characteristics, stride-to-stride variability, and knee flexion angle during use of the AMT two degree-of-freedom (2-DOF) elliptical and during use of a more traditional 1-DOF elliptical, and compare these to treadmill jogging.

3. VIDEO ANALYSIS OF ELLIPTICAL AND TREADMILL EXERCISE

To compare the kinematic patterns of the two kinds of elliptical training to treadmill jogging, experiments were performed on the three exercise machines (the AMT 2-DOF elliptical, the EFX 1-DOF elliptical, and a standard treadmill) at three different paces. The experimental analysis consisted of three parts: video acquisition of the exercise activities, image processing of the videos in Matlab, and subsequent analysis of the marker trajectories used to characterize the lower limb kinematics.

3.1 VIDEO ACQUISITION FOR KINEMATIC DATA COLLECTION

In this study, video analysis was conducted on two kinds of elliptical machines and on a treadmill. The two kinds of elliptical machines used were the 2-DOF Precor Adaptive Motion Trainer (AMT) and the 1-DOF Precor EFX 556i, described in detail in section 2.2. Experiments were carried out at three self-selected paces at low, intermediate, and maximum exertion levels, resulting in a slow, medium, and fast pace. On the fixed path elliptical trainer, trials were carried out at 50.50±1.14, 68.20±0.57, and 77.70±0.39 strides per minute. On the free form elliptical trainer, trials were carried out at 47.31±0.38, 50.27±0.35, and 52.40±0.46 strides per minute. On the treadmill, trials were carried out at 67.40±0.62, 68.58±0.73, and 72.47±0.54 strides per minute. Trials consisted of one minute of training. The subject was allowed five minutes rest in between trials to avoid fatigue. Video was captured with the Sony HDR-SR8 handycam at 30 frames per second. The camera was mounted on a tripod and placed approximately 3 meters from the exercise machine. The camera was oriented to capture the subject’s right profile from below the foot to just above the navel. Three adhesive green markers of approximately 35.00±2.29 mm diameter were placed on the subject’s right leg at anatomical landmarks. The ankle marker was placed on the lateral malleolus, the knee marker was placed in the joint space between the lateral tibial plateau and the lateral femoral condyle, and the hip marker was placed on the greater trochanter in order to track the desired anatomical orientation of the limb segment. The distance between the ankle and knee markers and the knee and hip markers was measured using a tape measure, and was approximately 39 cm and 44 cm respectively.

Figure 5 shows a sample of the raw image acquired by the video camera for each of the three types of exercise training. In the figure, the green markers used to track the translation and orientation of the limb segments are shown.

3.2 IMAGE PROCESSING IN MATLAB

In order to semi-autonomously track the locations of each marker, forty seconds of each video trial were uploaded into Matlab. Each frame of the video was stored as a 480 by 720 by 3 matrix of unsigned integers, where each entry of the matrix is a value between 0 and 255 representing the red, green, or blue intensity levels of each pixel in the frame. For each of the nine trials, approximately 1200 frames were stored in this format.

For each video clip, pre-processing parameters were determined by manually analyzing the video frames, including the red, green, and blue color threshold ranges for the markers and the vertical range of travel of each marker. The frames chosen were a forty-second interval
in the middle of the one-minute trials. The first and last frame of each trial was chosen at the lowest point in the stride for consistency in the stride analysis. The color thresholds for each video were determined experimentally using an open source Matlab code, which provided a graphical user interface to select desired pixels in a frame and determine the corresponding red, green, and blue intensity ranges of the pixels. The graphical user interface for this color thresholding technique is shown in Figure 6. This color thresholding technique was performed on all three markers for two to four randomly selected frames in each video and averaged to find a threshold value that could consistently isolate all three markers throughout the 1200 frames of each video clip.

A program was then written that uses the pre-processing parameters to autonomously locate the x and y position of the centroid of each marker (in pixels) and identify each marker (ankle, knee, or foot) based on its vertical position in the frame. Each frame in the desired range of the video clip was converted to a binary image by converting all pixels outside the desired color intensity ranges to black and all pixels inside the desired color intensity ranges to white. Marker pixel areas ranged from approximately 35 to 60 pixels, while background noise in the image ranged from approximately 1 to 25 pixels. An area threshold of approximately 30 pixels was chosen to eliminate background noise and consistently identified the unobscured green markers. Each marker was then identified as the ankle, knee, or hip marker by the vertical range of its centroid in the frame.

Figure 7 shows a sample cropped image and its corresponding thresholded binary image with the markers identified. In the binary image, the yellow dashed lines represent the divisions between the expected vertical ranges of each marker. The blue, green, and red dots represent the program’s successful identification of the x and y position of the hip, knee, and ankle marker respectively.

As the markers were loaded, visual feedback was provided to assure that the program consistently identified markers correctly. An example of the visual feedback provided is shown in Figure 8. Every twelfth frame was...
shown with marker positions superimposed on top of the original cropped image. If markers were incorrectly identified, the pre-processing parameters were revisited and modified until all markers were correctly identified.

As the markers were identified, their x and y positions were stored in a vector. A corresponding time vector was created based on the frame acquisition rate of 30 frames per second. In some cases, the elliptical stride, the Gauss occluded the markers during part of the stride. These markers and their corresponding times were omitted from the marker trajectory and time vectors.

### 3.3 Marker Trajectory Analysis

Once the image processing was complete, the raw marker trajectories were obtained in pixels. The raw marker trajectories were further processed to find the knee flexion angle and stride characteristics. The trajectory of the ankle marker was used to divide all marker trajectories into individual strides and to characterize the stride. The knee and hip marker trajectories were then also divided based on the starting and ending time of each stride. A conversion factor from pixels to meters was experimentally determined by finding the average pixel distance between the ankle and knee markers and dividing this by the measured distance between the two markers in meters.

The stride “length”, “height”, and “tilt” were estimated by fitting an ellipse to the ankle trajectory for each individual stride using least squares minimization techniques. A tilted ellipse not centered at the origin can be parameterized in the following vector form:

\[
\begin{pmatrix}
  x \\
  y 
\end{pmatrix}
= \begin{pmatrix}
  x_0 \\
  y_0 
\end{pmatrix}
+ \begin{pmatrix}
  \cos \alpha & -\sin \alpha \\
  \sin \alpha & \cos \alpha 
\end{pmatrix}
\begin{pmatrix}
  a \cos \theta \\
  b \cos \theta 
\end{pmatrix},
\]

where \(x_0\) and \(y_0\) are the x and y position of the centroid respectively, \(\alpha\) is the tilt angle of the ellipse measured counterclockwise from the long axis of the ellipse to the horizontal axis, \(a\) is the semi-major axis, \(b\) is the semi-minor axis, and \(\theta\) is a parameter that varies from 0 to \(2\pi\). For the AMT and EFX elliptical strides, the sum of squared perpendicular errors was minimized using a nonlinear Gauss-Newton algorithm. For the treadmill strides, the Gauss-Newton algorithm did not converge, so the sum of squared vertical errors was minimized instead using linear techniques. In this case, the function to be fitted is of the conic form:

\[
x^T Ax + b^T x + c = 0,
\]

and the sum of squared vertical errors are minimized subject to the Bookstein constraint, which says that the sum of the squared eigenvalues of \(A\) must equal 1. These curve-fitting techniques were implemented using an open source Matlab code. The stride length was estimated as the length of the major axis of the ellipse. The stride height was estimated as the length of the minor axis of the ellipse. Figure 9 shows the strides for each type of exercise at each speed, which are centered at the centroid of the least squares ellipse fit, and a sample average least squares fit for the AMT stride at medium speed.

The knee flexion angle was found by subtracting the horizontal and vertical position of the knee and ankle marker and the hip and knee marker to find the corresponding vectors that point along the mechanical axis of the tibia and femur, respectively. The dot product was taken of the anterior pointing vector perpendicular to the mechanical axis of the tibia and the vector pointing along the mechanical axis of the femur, which resulted in the negative of the knee flexion angle, according to equation 2.

A pictorial representation of the vectors used to determine knee flexion angle is shown in Figure 10. In the diagram, \(j\) is the unit vector along the anterior pointing axis of the tibial coordinate system and \(K\) is the source Matlab code.

![Figure 9](image)

**Figure 9:** The trajectory of the ankle marker is shown for all speeds during training on the EFX 1-DOF elliptical in Figure 9A, during training on the AMT 2-DOF elliptical in Figure 9B, and during treadmill jogging in Figure 9C. An ellipse was fit to each individual stride using least squares regression to estimate bulk stride characteristics. An average ellipse fit for the AMT 2-DOF stride is shown in Figure 9D. Stride length was estimated as the long axis of the ellipse and stride height as the short axis of the ellipse. The strides were centered using the centroid from the ellipse fit in Figures 9A-C.
unit vector along the mechanical axis of the femur coordinate system. According to the simplified definition of the knee flexion angle described in equation 2 in section 2.2, the knee flexion angle becomes the angle of the tibia relative to the long axis of the femur. As the knee bends, the flexion angle increases. Thus, the maximum knee flexion angle represents maximum knee flexion and the minimum flexion angle represents maximum knee extension.

4. RESULTS

Stride characteristics and knee flexion angle were determined for one trial each at three different paces on the three exercise machines (a total of 9 trials). Stride characteristics, including stride length, stride height, and stride tilt angle were estimated using a simplified least squares regression to fit the trajectory of the ankle marker to an ellipse. The knee flexion angle as a function of time was determined using the trajectories of the ankle, knee, and hip markers, as described in Section 3. However, the knee and hip markers were consistently obscured by the elliptical trainers during approximately 20-30% of the stride for the AMT 2-DOF elliptical trainer and approximately 5-10% of the stride for the EFX 1-DOF elliptical trainer. Knee flexion angles were not reported during these portions of the stride. Based on qualitative analysis, it is possible that this results in an underestimate of the maximum knee flexion angle for the AMT 2-DOF elliptical trainer.

4.1 STRIDE CHARACTERISTICS

The stride length and stride height for the three exercise machines at the three different paces are summarized in Table 1. Confidence intervals shown in the table are one standard deviation. The average stride length and height are also shown graphically in Figure 11. For each type of exercise, statistical comparisons of stride length and height were made between the different speeds using Tukey’s HSD (honest significant difference) test, using the pace (‘fast’, ‘medium’, or ‘slow) as the treatment group. Statistical comparisons of stride length and height were also made between the different types of exercise at the maximum exertion level using Tukey’s HSD test with exercise type (‘Treadmill’, ‘AMT’, or ‘EFX’) as the treatment group. Although the stride frequency was not the same for each type of exercise, the stride during the ‘fast’ pace was assumed to be the maximum possible because the subject was exercising at maximum exertion. All uncertainties stated are one standard deviation and did not include uncertainty due to measurement error, which is estimated to be ±0.017m, half the diameter of the markers used.

At the slowest pace, both the AMT 2-DOF elliptical trainer and the EFX 1-DOF elliptical trainer showed similar stride lengths to low speed treadmill jogging, with stride lengths of 0.463±0.018 m for the AMT elliptical, 0.457 ± 0.007 m for the EFX elliptical, and 0.524 ± 0.021 m for treadmill jogging. As speed increased from the slowest pace to the fastest pace, the stride length in both

<table>
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<th>Table 1: Mean values for stride characteristics on the three exercise machines.</th>
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AMT elliptical training and treadmill jogging increased significantly (p<0.05). Tukey’s test also showed a statistically significant increase in stride length from slow to fast in the EFX elliptical training; however, because this difference (0.006±0.004 m) is smaller than half the diameter of the markers used in the experiment (0.017±0.001 m), it was considered insignificant within the measurement error. From the slowest to the fastest pace, the jogging stride length increased by approximately 50% to 0.768±0.136 m. From the slowest to the fastest pace, the AMT elliptical stride length increased by approximately 20% to 0.551±0.006 m, which is 70% of the maximum jogging stride length, which is significantly smaller (p<0.05). The maximum EFX elliptical stride length was significantly smaller than both the jogging and AMT elliptical strides (p<0.05), at approximately 60% of the maximum jogging stride length and approximately 80% of the maximum AMT elliptical stride length.

Only the jogging stride height changed significantly with an increase in speed (p<0.05). At all speeds the stride height was the greatest in the AMT elliptical at 0.284±0.014 m, which was approximately 150% of the maximum jogging stride height (0.185±0.047 m). At all speeds the stride height was the smallest in the EFX elliptical at 0.100±0.009 m, which was approximately 50% of the jogging stride height. The stride tilt angles were positive for both treadmill jogging and AMT elliptical training, corresponding to a downward stride tilt, while the stride tilt was negative in the EFX elliptical training, corresponding to an upward tilt.

Stride-to-stride variability is seen in the spread of the stride length and height probability density functions, which are shown for all exercise types in Figure 12. The probability density functions have a roughly Gaussian distribution. As seen in the figure, treadmill jogging had the highest standard deviation of stride length, which

![Figure 11](image1.png)

**Figure 11:** Top: a bar graph displays the average stride length in meters. Bottom: a bar graph displays the average stride height in meters. An asterisk indicates a significant increase from slow to fast pace for a particular exercise type (p<0.05).

![Figure 12](image2.png)

**Figure 12:** The stride length probability density function is shown at slow, medium, and fast pace for EFX elliptical training in Figure 12A, for AMT elliptical training in Figure 12B, and for treadmill jogging in Figure 12C. The stride height probability density function is shown at slow, medium, and fast pace for EFX elliptical training in Figure 12D, for AMT elliptical training in Figure 12E, and for treadmill jogging in Figure 12F.
ranged from 0.136 m to 0.029 m. The standard deviation of stride length for the AMT and EFX was not significant, as it was smaller than half the diameter of the markers used in video analysis. The standard deviation of the stride height was not significant for any of the exercise modes except jogging, which had a maximum standard deviation of 0.047 m.

4.2 KNEE FLEXION ANGLE

For each type of exercise, statistical comparisons of maximum and minimum knee flexion angle were made between the different speeds using Tukey’s HSD (honest significant difference) test, using the pace (‘fast’, ‘medium’, or ‘slow’) as the treatment group. Statistical comparisons of maximum and minimum knee flexion angle were also made between the different types of exercise at the maximum exertion level using Tukey’s HSD test with exercise type (‘Treadmill’, ‘AMT’, or ‘EFX’) as the treatment group. Average maximum and minimum knee flexion angles during a stride are shown in Figure 13. At the highest speeds, the maximum knee flexion angle was significantly greater in AMT 2-DOF elliptical training (89.2 ± 0.2°) and treadmill jogging (88.1 ± 0.5°) than in EFX 1-DOF elliptical training (64.5 ± 0.7°) by almost 30 degrees (p<0.05). Only treadmill jogging had a significant increase in maximum knee flexion angle from low to high speeds, whereas the maximum knee flexion angle did not change significantly in either form of elliptical training. Minimum knee flexion angle, which corresponds to the maximum extension of the leg, was lowest in the EFX 1-DOF elliptical trainer (9.3±0.3°).

The knee flexion angle pattern throughout the stride was found by normalizing each stride by its duration and ensemble averaging to find the knee flexion angles as a function of the percentage of the stride. The ensemble average was obtained by finding the average of the knee flexion angle over 5% intervals for each stride and then averaging these 5% interval mean values over all strides. Figure 14 shows the ensemble averaged knee flexion angles as a function of percentage of stride for slow, medium, and fast paces.

For all speeds, treadmill jogging exhibited two peaks in knee flexion angle, a small peak during stance phase around 45° (0-30% of stride) and a larger peak during swing phase (30-100% of stride). For all speeds, AMT 2-DOF elliptical training resulted in a maximum knee flexion angle during swing and a minimum during stance. For all speeds, EFX 1-DOF elliptical training resulted in a maximum knee flexion angle during swing and a minimum knee flexion angle during stance. This pattern is consistent with the findings in a previous study that compared knee flexion angle in treadmill walking and elliptical training, shown in Figure 4, which can be found in section 2.2.  The knee is in high flexion for 10-20% longer in AMT 2-DOF elliptical training than in treadmill

![Figure 13](image1.png)

**Figure 13:** On the left: a bar graph displays maximum knee flexion angle in degrees. On the right: a bar graph displays minimum knee flexion angle in degrees. Error bars show standard error on a 95% confidence interval. An asterisk indicates a significant increase or decrease in peak knee flexion angle from slow to fast pace.

![Figure 14](image2.png)

**Figure 14:** Ensemble averaged knee flexion angles throughout stride for slow, medium, and fast pace exercise activity. Strides were normalized by duration and then knee flexion angles were time averaged over 5% intervals of each stride. The 5% interval mean values were then averaged over all strides. Disconnected lines indicate that marker data was not available during that 5% stride interval.
jogging, which is evidenced by the peak in knee flexion angle during swing in AMT 2-DOF elliptical training, which is wider than that of treadmill jogging.

5. DISCUSSION

As hypothesized, none of the EFX 1-DOF elliptical stride characteristics varied significantly with a change in speed. The stride length and height were much shorter than in jogging, and the stride tilt was actually in the opposite direction. The knee flexion angle followed a sinusoidal pattern, reaching a maximum in swing and a minimum in stance. This was unlike the pattern in treadmill jogging, which reached a peak during both stance and swing. The minimum knee flexion angle was smaller in this form of elliptical training, corresponding to a peak in knee extension during stance. It is unclear based on this analysis if these are negative qualities, but it is clear that this is a very different kinematic form of exercise than jogging.

The results for the AMT 2-DOF elliptical did not clearly agree with the hypothesis. Although the stride length did increase slightly with increased speed, it reached a plateau at a stride length that was approximately 70% of the maximum jogging stride length. This is attributed to the limited geometric workspace of the seven-bar linkage mechanism. The stride-to-stride variability was small, especially in the stride height and peak knee flexion angle. The stride height was much larger than in jogging, by approximately 150%. The peak knee flexion angle was very high independent of speed, and the knee was in high flexion for 10-20% longer than in jogging. These results were unanticipated and unsettling.

To explain these results, the seven-bar linkage mechanism was analyzed. A second look yielded the observation that a kinematic singularity occurs in the mechanism during swing phase. At this instant, when two linkages align, any rotation of the flywheel cannot change the first degree of freedom, $\Phi_1$. This means that the mechanism is instantaneously reduced to a single degree of freedom, that of $\Phi_2$, which prevents the natural downward swing of the leg. A schematic diagram of this is shown in Figure 15. As shown in the figure, the foot is forced along the trajectory given by $v$. This explains the large stride height, the large prolonged knee flexion, and the lack of stride height variability.

Figure 15: A schematic diagram of the seven-bar linkage mechanism in the AMT during swing, when a kinematic singularity occurs. At this point, rotation of the flywheel will not result in a change to the first degree of freedom, shown as $\Phi_1$. The mechanism is instantaneously reduced to one degree of freedom, that of $\Phi_2$. This prevents the natural downward swing of the leg by limiting the foot to the trajectory denoted by $v$.

The implications of this are unclear. While peak knee flexion angles were similar to jogging, the peak flexion in jogging occurs during swing, when the leg is naturally unloaded. A much smaller peak (approximately 50%) occurs in jogging during stance, the loaded portion of the stride. The peak knee flexion in the AMT is not unloaded, due to the constraint and impedance of the elliptical mechanism. Although force data was not collected, it is hypothesized that this forced flexion creates a knee joint stress that is much larger than would be expected or desired from a low impact form of exercise.

One unpublished study that measured the kinematics and kinetics of elliptical training on the AMT supported this hypothesis. This study found that the highest knee joint stresses occurred during swing, and were of similar magnitude to the knee joint stresses experienced in lunging and stair-climbing, which are activities that should often be avoided for people with chronic knee pain or injury.

6. CONCLUSION

This study measured the sagittal plane kinematics of the lower limbs during elliptical and treadmill exercise. In particular, the analysis focused on bulk stride characteristics, stride length and stride height, and the
knee flexion angle. It was found that the traditional one degree-of-freedom (1-DOF) elliptical stride did not vary with speed or from stride to stride, and that the stride length and height were much smaller than that of treadmill jogging, by about 60% and 50% respectively. It was found that the novel AMT 2-DOF elliptical stride varied somewhat with speed and from stride to stride, but the stride length was smaller than in jogging by approximately 70% and the stride height was much larger, by approximately 150%. The peak knee flexion angle was also very high and independent of speed. These findings were attributed to a kinematic singularity in the mechanism, which forced the knee into prolonged flexion during swing. The implications of this are not entirely clear.

Further studies should measure and compare the three dimensional reaction forces and moments on the foot in the three forms of exercise, especially in the AMT 2-DOF elliptical trainer. This data can be combined with kinematic data to explore the effect that the altered kinematics have on knee flexion moment and ground reaction force. An ideal form of elliptical training would create a stride similar to a natural jogging stride, without the high joint stresses experienced in jogging. For someone rehabilitating from surgery or injury, a ground reaction force and knee flexion moment of similar magnitude to jogging would be undesirable. Still, the design of an engaging and dynamic elliptical machine may be possible, and despite its flaws, the AMT seems to be a step in the right direction. Clever adjustments to the mechanism design may enable the design of a machine with a truly adaptable, natural stride without the disadvantage of high joint stresses.

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