### A Wearable Gait Analysis System for Overstriding in Runners

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A Wearable Gait Analysis System for Overstriding in Runners

by

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ES 100 Senior Capstone Project Report submitted to the School of Engineering and Applied Sciences in partial fulfillment of the requirements for the degree

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Abstract

As interest in running continues growing, runners are constantly seeking ways to prevent common aches and injuries. Gait retraining to improve the biomechanics of running can affect the forces experienced by the body, and is hypothesized to lower the chance of injury and improve running efficiency. However, existing gait retraining methods rely heavily on external equipment and human analysis, meaning it is not accessible for everyday runners. The wearable gait analysis system highlighted in this project is designed to monitor running gait without external equipment, thus shifting gait analysis out of training centers and giving runners the opportunity to correct their gait independently. This project features IMU technology to specifically target and reduce overstride in runners. By monitoring the shank angles throughout the cycle and determining the overstride angle at time of impact, the system is able to measure overstriding with fewer than 3° of errors across a variety of speeds and running styles. This measurement is then translated into live-time feedback for runners.
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1 Introduction

1.1 Motivation

Despite its growing popularity, running continues to report exceptionally high injury rates compared to other popular fitness activities, with middle-range estimates reporting approximately 66% of runners who are injured each year.\(^1\) Injuries in the lower extremities are most common, with reported incidence rates up to 79.3%. The predominant site for these injuries is the knee, with the most frequent complaint being patellofemoral pain, commonly known as “runner’s knee”.\(^2\) While the exact cause behind the high rate of running injuries has not yet been proven, a supported belief is that changing the mechanics of running form can play a large role in injury prevention. For example, increasing stride frequency (SF) while maintaining a constant horizontal velocity leads to a subsequent decrease in stride length (SL), which is believed to reduce the horizontal component of the ground reaction force (GRF) experienced by the body upon impact.\(^3\) Prior work has supported this idea by showing that increasing SF by 110% at a constant velocity, therefore decreasing SL, leads to a reduction in the peak patellofemoral joint force by 14%, which could be instrumental in lowering the incidence of patellofemoral pain.\(^4\) As a result of these studies, landing with the foot closer to a runner’s center of mass (COM) is believed to be beneficial in reducing injury, and has become a large focus of gait retraining. This correction has been termed “reducing overstride.”

Though most experts and running coaches agree that reducing overstride is beneficial, there are currently limitations to the existing methods addressing this problem.
Most notably, existing gait retraining methods require bulky equipment and human analysis, meaning they are non-portable processes. Runners are limited to lab conditions, often running on a treadmill. Because of this non-portability, there is also a lack of extensive studies on overstriding in natural running environments, since it is difficult to control and monitor running gait outside of lab data collections.

This project seeks to address both of these problems by designing and evaluating a wearable gait retraining system that targets the correction of overstriding. By coupling a system of sensors with studies of the running gait cycle, it was possible to design a portable feedback system that provides real-time overstriding feedback to the runner. This allows the runner to correct his or her gait immediately, without depending on bulky equipment or a human trainer. Because this system can function outside of lab conditions, there are significant implications for biomechanical research as well.

1.2 Existing gait retraining methods

Gait retraining is a gradual process that requires constant monitoring and adjustments over time. Examples of existing techniques include visual training, where a runner runs on a treadmill using mirrors for feedback,

verbal feedback, where a coach or trainer observes a runner’s gait and provides instruction,

and post-activity analysis, which involves capturing a run with high-speed cameras or motion capture systems, and analyzing gait patterns after the run is complete. Examples of post-activity analysis are depicted in Figure 1.
Because of this dependence on extensive equipment, gait retraining often cannot exist outside of specialized training centers and labs. As a result, runners are unable to independently receive accurate feedback on their running form outside of training sessions, and are limited to the sessions they schedule. Additionally, the non-portability of gait retraining introduces the additional problem of artificiality, which can impact results. Instead of running in natural environments, runners are constrained to artificial treadmill settings, which may lead to differences in gait patterns. Consequently, any analysis that occurs in a lab is not necessarily representative of natural running conditions.

1.3 Defining overstride

As mentioned, reducing overstride is a popular component of gait retraining, with the general consensus being that it is biomechanically desirable to reduce overstride as
much as possible. Overstriding can be defined as the distance forward in the sagittal plane the foot lands relative to the COM, which is often approximated as the point between the hips, as illustrated in Figure 2. In addition to hypothesized benefits of injury prevention, there are benefits associated with energy efficiency. By reducing overstriding and landing with one’s foot closer to the COM, a runner decreases the magnitude of the braking force experienced by the body, thus minimizing the forces that slow one down.\textsuperscript{viii} This lowers the propulsive force the body needs to generate in order to maintain steady motion, resulting in increased energy efficiency. Additionally, by landing with one’s foot directly under the COM, the runner is able to take better advantage of the elastic recoil energy that is gained by treating the leg like a vertical spring.\textsuperscript{ix} When all these measures are taken into account, it is reasonable to conclude that reducing overstriding is likely to offer multiple benefits to runners, explaining why it is a frequently targeted metric in gait retraining.

\textbf{Figure 2. COM definition of overstriding.} Figure 2 illustrates the concept of overstriding, which is derived from the projected difference between the foot and the COM, represented by the thick yellow line. Projected distances want to be minimized as much as possible to reduce the horizontal GRF force experienced by the runner. A projected difference of 0 or below is considered acceptable overstride.
Because it can be difficult to measure the projected distance from the COM to the foot without motion capture, an alternative method of defining overstriding is to evaluate the distance forward between the knee and the foot upon. This is often evaluated by looking at the angle the shank, or tibia, makes relative to the vertical. An illustration of the shank angle measurement is shown in Figure 3. A positive shank angle is indicative of too much overstride, and is considered biomechanically undesirable. A zero or negative angle is considered better form. In general, smaller overstride angles indicate the foot is landing closer to the COM, and correspond to better form.

![Figure 3. Angular definition of overstriding](image)

Figure 3. Angular definition of overstriding. Figure 3 illustrates the concept of overstriding. A positive shank angle (yellow) relative to the vertical is indicative of too much overstriding. A neutral or negative overstride angle is considered to acceptable overstride, and is associated with good running form.

This method of defining overstride is much more prevalent among running coaches and training centers that do not use extensive motion capture software, because it is easier to visually evaluate, as opposed to measuring projecting distances between body parts. However, both definitions of overstride were initially evaluated in the design of the project.
2 Design requirements

While designing a wearable system to measure overstride, there were multiple design requirements to consider. Firstly, the system must be able to monitor the motion of human running accurately, especially around the time of impact where overstride is defined. In general, if one uses the shank angle definition of overstride, the observed overstride range is between $-20^\circ$ to $20^\circ$, though available data is based largely on observations from running coaches.\textsuperscript{xii} Within this range, it is not critical to determine the exact angle that the runner is landing at, and many coaches approximate the overstride angle by a degree or two.\textsuperscript{xii} However, an error of about $3^\circ$ starts to become significant, as many coaches comment on differences between overstride angles that differ by $3^\circ$.\textsuperscript{xiii}

To fulfill this requirement of accurately tracking human running, not only must the system report overstride values within $3^\circ$ of truth, but it must also operate at an appropriate sampling rate. Currently, most gait analysis is conducted in labs with the ability to operate at high sampling rates without much cost; thus, it not uncommon to see studies conducted at 100 Hz without any problems in the kinematic data. However, it may not be necessary to sample at 100 Hz. It has been shown that basic walking motions can be tracked with as little as 10 Hz,\textsuperscript{xiv} and studies on the lower extremities have been conducted at 50 Hz on a VICON system during running, sidestepping and crossover cuts without major issues.\textsuperscript{xv} It has been suggested that most aspects of gait can be measured comfortably at 25 Hz.\textsuperscript{xvi} For this project, the target sampling rate was set to be a minimum of 25 Hz, with the caveat that this value needed to be verified with testing. As
will be shown, a 25 Hz sample rate is overall sufficient, but could be increased for better results.

An additional design requirement is that the system cannot interfere with the regular biomechanics of running. Forces across moving joints must be minimal to non-existent, especially around the knee, which experiences frequent flexion and extension during running. The system should be lightweight, fewer than 5 ounces, and comfortable to wear. The system also cannot be subject to movements that interfere with its performance, nor should any movements of the system distract the runner.

Lastly, due to the high variability in running, the system must also be able to operate at a variety of speeds above 1.8 mps, the transition from walking to running. For this project, an upper limit of speed was set at 3.8 mps (8 mph) with the understanding that the running speed of an average everyday runner is likely to fall within these values. The system must also be able to operate across subjects with different striking techniques. Strike techniques are commonly divided into forefoot strike (FFS) and rearfoot strike (RFS). Runners who run with a FFS run with the balls of the foot contacting the ground before the heel, and runners with a RFS run with the heel contacting the ground first. The different strikes are illustrated in Figure 4.
Figure 4. Forefoot strike (FFS) vs. rearfoot strike (RFS). Figure 4(a) shows the runner about to land on the ball of her foot before her heel. Figure 4(b) shows the runner about to land with her heel first.
3 Selection of technology

Four existing technologies were considered as options for the system: soft strain sensors, goniometers, IMUs, and proximity sensors, which are depicted in Figure 5.

![Figure 5: Overview of existing technology. Figure 5(a) shows a soft strain sensor, 5(b) a traditional goniometer, 5(c) an IMU, 5(d) electromagnetic tracking system](image)

The first option involved modifying and designing around soft strain sensors, which consist of liquid metal microchannels (EGaIn alloy) embedded in silicon. When the sensors are stretched, the conductivity and resistivity of the sensors change, making it possible to determine the strain experienced by the sensor. As a result, joint angles could be calculated by extending a sensor across joints and evaluating the resulting change in strain during joint movement. It was believed that various joint angles, such as the hip-
thigh angle and the thigh-tibia angle, could be combined in a way to approximate overstride.

Designing a goniometer was evaluated as another option. One possibility was to use a potentiometer that sits at the side of the knee, with arms that run down the tibia and femur to measure the knee angle, bearing in mind that rigidity would have to be eliminated as much as possible. Another possibility was a telemetric goniometer, which would have two coils and an articulation point. Signal could be applied at one end, and the induced voltage measured at the other. By knowing the distance between the coils and the articulation point, angles could be calculated from the signal.\textsuperscript{ix}

Inertial Measurement Units, or IMUs, were the third option considered. IMUs are sensor units consisting of accelerometers, gyroscopes, and sometimes magnetometers. Accelerometers are used to measure acceleration and tilt, gyroscopes are used to measure angular velocity, and magnetometers help provide orientation and direction information. The combination of these devices and manipulation of their data allows for the calculation of acceleration, speed, and position. One potential problem with IMUs is that the data can be noisy for certain types of motion, which was factored into the decision process.

The last option that was briefly considered involved the use of an electromagnetic tracking system that could be used to detect the position of marked points. For these systems, accuracy is pretty high in close ranges of about 8-24 inches. However, this system is not very portable, due to the requirement of a field generator\textsuperscript{x}. Overall, a summary of advantages and disadvantages of the four options is summarized in Figure 6. After evaluating the options in depth, it was decided that IMUs
would be the best viable option, due to their low profile and portability. However, testing would have to be done to ensure that the quality of data provided by an IMU would be sufficient for the application of measuring overstride.

Figure 6: Summary of existing technologies

<table>
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<tr>
<th>Design consideration</th>
<th>Soft strain sensor&lt;sup&gt;xxi&lt;/sup&gt;</th>
<th>Goniometer&lt;sup&gt;xxii&lt;/sup&gt;</th>
<th>IMUs</th>
<th>Proximity sensing&lt;sup&gt;xxiii&lt;/sup&gt;</th>
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<td>Accuracy</td>
<td>Maximum RMS error of 15° for a running speed of 2.7 mps</td>
<td>Telemetric goniometer has max. error of 6° in range between 20-120°</td>
<td>Depends on the application. May have very high accuracy but subject to noise and drift.</td>
<td>Accurate within a close range of 8-24”.</td>
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<td>Portability</td>
<td>Reasonable. Requires attachments to body on both sides of relevant joint.</td>
<td>Moderate. Requires potentially rigid components</td>
<td>High. Lightweight profile</td>
<td>Low. Not portable due to reliance on field generator</td>
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<td>Interference with natural biomechanics</td>
<td>Low. Restrict wearer by less than 0.17%,</td>
<td>High. Requires a potentially rigid attachment across moving joint</td>
<td>Low. Does not require any attachments across moving joints.</td>
<td>Low. Heavy and bulky field generator required</td>
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3.1 Prior Art

In terms of prior art that relates to IMUs, there has been some progress towards making a more portable gait analysis system using a combination of inertial sensors; however, none accomplish the goals of this project. One of the most notable examples is an IMU “suit”, such as the Xsens Biomech system, which uses 17 MTx inertial motion trackers that communicate with a master processor. This master processor combines the information from multiple sensors to recreate motion on a laptop. While this is more portable than lab equipment, these suits are still currently limited to a wireless range of about 500 feet. xxiv The technology also requires separate software and human analysis to process the data, and costs about $75,000. Consequently, one of the major goals of this project was to see if it were possible to design a much simpler and lower-cost alternative to these suits for measuring overstride.

Figure 7: Xsens system. Multiple IMUs are worn on the body in the form of a “suit.” Data is visualized on a computer.
It has also been proposed to place devices that comprise of accelerometers and gyroscopes in the shoe, as shown in Figure 8. These devices can be used to measure foot movements and derive gait kinematics such as velocity, pronation angles, and impact upon landing. One such system, which has been patented but has not publicly disclosed results, suggests taking the acceleration data from both shoes and comparing them to each other to determine overstride. This acceleration data is compared to a pre-collected overstride motion profile, which is configured by each user individually. However, this approach relies heavily on an involved pre-calibration process that may be difficult to regulate. Another goal of this project was to determine if there were a more reliable and universal way to measure overstride that would apply across many subjects.

**Figure 8 IMUs in shoes.** Figure 8 highlights the placement of an accelerometer on the shoe, which can be used to calculate running velocity and overstride. A tilt sensor can also be incorporated to monitor pronation angles.
4 Overview of System Design

After taking into account existing IMU technologies and the stated design requirements, the system shown in Figure 9 was developed.

Figure 9. System Design. An IMU is attached to the anterior tibia and is programmed to calculate the shank angle relative to the vertical throughout the stride. The microcontroller processes this data and calculate the relevant overstride angle at impact, which is then communicated to the runner via wrist-worn feedback.

The system consists of a single 9-degree of freedom IMU attached to the runner’s anterior medial tibia via a compression sleeve, which is designed to measure the shank angle at impact, in accordance with the popular angular definition of overstriding among running coaches. This was chosen over an alternate design that incorporated multiple IMUs at the hips, thigh, and tibia that would attempt to approximate the distance of the foot from the COM, because of its increased simplicity and lower risk for errors. By
measuring angles instead of double-integrating acceleration to get position, the accumulation of errors would be less severe. Additionally, by using a single IMU instead of multiple, computational needs were reduced. The IMU at the tibia originally made the assumption that all significant angular changes occurred in the sagittal plane of the runner, and the relevant angle was taken to be the angle around the x-axis of the IMU.

This angle is highlighted in Figure 10. As will be verified in tests, this assumption ended up being valid, and no further sensors were required to measure overstride.

**Figure 10. Angle of relevance.** The shank angle in the sagittal plane 10(a), as well as in the angled view 10(b), is shown as the angle of relevance. The angle is measured using the gyroscope data from the IMU to read the angle around the x-axis.
In terms of attachment, the IMU was sewn into the compression sleeve, which is worn around the tibia. This method of attachment was selected over strapping mechanisms, fabrifoam, or Velcro, due to its ability to hold the IMU motionless over the course of a longer run.

The data from the IMU is processed by a microcontroller, which can be attached to the user’s hip using a waist pack. The microcontroller uses the data to calculate the relevant overstride angle at impact by using known patterns in shank angles throughout the gait cycle, which were obtained and derived through empirical research during system development. This data can then translated into feedback, which is delivered back to the runner.

4.1 IMU Selection

The most critical component of the system is the IMU, as it is responsible for the data generation. As a result, many tests were conducted to ensure the sensor would help the system meet the design requirements. The Razor 9DOF IMU was selected for its high accuracy to cost ratio. This IMU incorporates a triple-axis ITG-3200 Gyroscope, triple-axis ADXL345 Accelerometer, and a triple-axis HMC5883L magnetometer.\textsuperscript{xxv} The outputs of the sensors are processed on-board and sent out to the microcontroller by UART communication. In order to validate the accuracy of the calibrated sensor, stationary tests were conducted on a constructed test rig, which is shown in Figure 11, as well as on a motionless leg. The IMU reading on the test rig was determined to have an accuracy of ±0.5°. For tests on a motionless leg, the IMU readings at multiple leg angles
were compared to the results of Kinovea, a video-analysis software that allows for the measurement of angles. These test yielded an accuracy of ±1°.

Figure 11. Stationary test rig. The IMU reading was placed at different known stationary angles and the readings were compared to actual values. Readings were accurate up to ±0.5°.
The IMU was updated with firmware that internally fuses the accelerometer, magnetometer, and gyroscope data using a Direction Cosine Matrix (DCM) algorithm. This algorithm corrects for sensor noise while requiring less computing power than the Kalman filter.\textsuperscript{xxvi} To verify the efficacy of this algorithm, a thirty-minute trial was conducted to evaluate IMU drift, which is when sensor outputs change over time, despite fixed input and operation conditions.\textsuperscript{xxvii} It was determined that the IMU was not subject to significant drift over the course of thirty minutes, as the reported values did not change.

Overall, the stationary tests suggested the selected IMU would be a suitable choice for the system due to its high accuracy. Later testing validated that the accuracy of the IMU on a moving leg is appropriate for gait retraining applications, with no more than a few degrees of average error while running. These results will be elaborated on in a future section.

4.2 Compression Sleeve Attachment

The IMU was sewn 10 cm above the bottom of the compression sleeve, which was worn by the runner such that the bottom edges of the sleeve lined up with the medial and lateral malleoli. The setup can be shown in Figure 12. In order to ensure that the attachment would remain stationary during an activity, an endurance test was conducted for the course of 10 minutes. During this time, the subject was asked to run at what he perceived to be a high speed (3.5 mps) and was encouraged to shake his leg while running. Post-trial stationary measurements were then compared to identical pre-trial
stationary measurements, and the reported values did not differ by more than 1°, showing the attachment mechanism is appropriate.

Over the course of the project, the compression sleeve attachment was also tested with over ten different subjects of varying leg length and diameters, with no noticeable differences in performance. Pre-trial and post-trial stationary measurements were taken during each data collection to ensure the system had not shifted during the trial.

Figure 12. Compression sleeve attachment. The IMU was attached the runner by a compression sleeve that was worn on the tibia. The bottom of the compression sleeve was lined up with the lateral and medial malleoli for consistency across subjects.
4.3 Feedback Mechanism

While the feedback component would be important for productization, the main focus of this project was not to productize, but instead to determine whether or not an IMU system could even accurately measure overstride. Other than a proof of concept, the feedback mechanism was designated a smaller component of the project, and time was instead spent on validating that the system would be able to accurately measure overstride over a variety of different conditions, and across different subjects. Since it will later be shown that overstride angles can be measured fairly accurately using this IMU system, future work can certainly work on using these reported overstride angles to expand on the feedback system, perhaps by including audio or haptic signals, increasing the granularity of feedback, or increasing the robustness of the feedback algorithm.

For the purpose of proving a concept, feedback is given to the user in the form of visual lighting, with a red LED indicating excessive overstride, a yellow LED indicating moderate overstride, and a green LED indicating no overstride. In order to minimize the effects of temporary irregularities, such as missteps or obstacles in the road, the system evaluates overstride angles over the course of a 5-stride window to determine overall level of overstride based on a set of conditions. Exact coding for the algorithm can be found in the Appendix.

In terms of determining the upper and lower thresholds for the various levels of overstride, the system is designed using generally accepted values of overstride angles. If the shank angle at impact is consistently below 0°, the system maps this to “no overstride.” Consistent overstride angles between 0° and 7° degrees are considered to be “moderate overstride”, and angles above 7° are considered to be “excessive overstride.”
While these values are currently popular in the running community and consistent with the belief that reducing overstriding as much as possible is beneficial, it is worth noting that these values have not yet been proven through extensive research. As mentioned earlier, the inability to conduct studies outside of artificial lab environments has limited the studies that can be conducted on overstriding. However, perhaps the portable design of this system will allow for allowing more research to be done in order to determine the proper boundaries of overstride. The system can be easily updated with different threshold values as necessary.
5 Preliminary Explorations

5.1 Comparison with motion capture

The first major component of testing was to ensure that the designed system could accurately track shank angles over the course of the running cycle, so that the angle at impact could be identified. In order to test and develop the system, tests were run in a marker-based motion capture lab, which is considered a golden standard in tracking human motion. The lab was equipped with a custom treadmill (Bertec, OH) instrumented with two force plates to measure GRF at 1000 Hz, as well as 8 infrared cameras that captured 3D motion data at 100 Hz (Qualysis Corp, Gothenburg, Sweden). Thirteen reflective markers were placed in the following biomechanical landmarks: the right and left anterior superior iliac spines, the right and left posterior superior iliac spines, the right greater trochanter, the medial and lateral epicondyle of the right leg, the anterior tibia of the right leg, the medial and lateral malleoli of the right leg, the calcaneus of the right foot, and the first and fifth metatarsal heads of the right foot. Figure 13 depicts the setup of the lab.

The marker data captured from Qualisys was processed in Visual 3-D, where knee and ankle landmarks were derived from the medial and lateral epicondyles, and the medial and lateral malleoli. These two landmarks were joined to represent the shank. A third vertical vector in the z-direction was also introduced which dropped directly from the knee landmark. The shank angle was calculated as the angle between this vertical landmark and the shank.
Figure 13. Motion capture lab. Subjects were outfitted with 13 markers in biomechanical landmarks which are partially shown in Figure 13 (a). The medial side is not pictured. All trials were conducted on an instrumental treadmill as shown in Figure 13 (b), with two force plates beneath the moving belts.
The IMU system was synched directly to the motion capture system by connecting a modified BNC cable to the A/D board. More details on the synchronization process can be found in the Appendix. The IMU data was then compared with a reconstructed profile of the runner’s motion derived from Qualisys and Visual 3D, allowing a direct comparison between the overstride angles calculated by the IMU system and the motion capture. In both cases, the shank angles curve throughout each step followed the same cyclic shape, which is illustrated in Figure 14 on the following page. Both the IMU and motion capture models were set up such that positive shank angles represent the time when the foot is in front of the knee, and negative shank angles represent the time the foot is behind the knee. Video footage was used to map the various stages of the running gait cycle to the shank angle cycle, which are also illustrated in Figure 14.

Initial contact (IC) represents the point in time where the foot first contacts the ground. Toe-off (TO) is defined as the final point of contact before the foot lifts from the ground.
Both the IMU and Qualisys motion capture system reported similar shank angle cycles for each step, which is illustrated above. The various stages of the running cycle have been mapped onto the shank angle cycle as a reference.

Figure 14. Shank angle cycle. Both the IMU and Qualisys motion capture system reported similar shank angle cycles for each step, which is illustrated above. The various stages of the running cycle have been mapped onto the shank angle cycle as a reference.
A comparison of the angles across three strides from the IMU system and motion capture are shown below in Figure 15, which was used to determine how accurately the IMU system measures shank angles.

The mean average error was determined to be 3.97° across these three steps. However, it was noticed that the error of the IMU system consistently decreases around the areas of positive slope, while increasing in other parts of the shank angle cycle.

By comparing Figures 14 and 15, it can be seen that most of the error comes from the stance phase, the second float phase, and the part of the swing phase where the shank angle is still decreasing. These are all phases where the shank angle is changing faster, either due to contact with the moving belt of the treadmill during stance, or due to the quick motion the runner makes in order to swing his foot up and behind him. In the
second half of the swing phase, once the runner begins swinging his foot forward at a slower speed, the accuracy becomes much better, with a mean average error of 1.5°, which is suitable for the purposes of overstride detection. This increase in accuracy persists to the area around initial contact. The likely reason for this difference in errors is that the maximum achievable sampling rate of the IMU, which is 27 Hz, cannot capture the faster parts of the running gait cycle with as much accuracy as the motion capture system running at 100 Hz.

Despite the slight decrease in accuracy in parts of the stance and swing phases, the IMU system is still able to measure the angles preceding and around initial contact well enough for the purposes of determining the degree of overstride, since the relevant angle is the shank angle at initial contact. This performance is consistent at higher running speeds, showing similar accuracies in the relevant areas for speeds up to 3.58 mps (8 mph), the highest speed that was tested. As a result, it was decided that the system with a sampling rate of 27 Hz was appropriate for the purpose of monitoring overstride at initial contact, though an IMU with a higher sampling rate could and should be evaluated for future projects. It was also decided that the assumption that all relevant motion is happening in the sagittal plane would be valid for measuring overstride angles.

5.2 Using the force plate to determine initial contact

The second component of testing was to determine exactly when initial contact occurs, so that the shank angle could be recorded at that point and used to determine overstride. In the lab, the force plate data could be used to determine the exact time of initial contact. However, the IMU system on its own obviously cannot rely on a force
plate reading. In order to determine IMU data patterns at initial contact that could be incorporated into the system, the force plate data was examined against shank data to study patterns at the time of impact. The raw force plate data was filtered with second-order Butterworth lowpass filter, designed with a cutoff frequency of 250 Hz, before it was used in analysis. With the introduction of the filter, the noise was significantly reduced from a magnitude of about 20-30 N to 8 N, such that it was possible to set an initial contact threshold of 10 N without false positives from noise. The points of initial contact are represented by the green dot in Figure XYZ below, along with the raw and filtered force plate data for two strides.

**Figure 16. Force readings and initial contact**
The relevant shank angle was then extracted at the time associated with initial contact in order to determine overstride angle. Because the sample rate of the force plate was higher than both the motion capture and IMU systems, linear interpolation was used to determine the relevant value if the time indices did not match. Figure 17 shows a graphical comparison of the force plate data and the shank angle data for two strides at 3mps. Results shown are consistent across the entire trial. The dotted line connects the time of initial contact as determined by the force plate data to the shank angle data. The overstride angle is the shank angle at the time of contact, as represented by the red dots.

**Figure 17. Force reading and shank angles (3 mps)**
From this data, we qualitatively see that initial contact consistently happens around the peak of the shank angle cycle, and we can hypothesize that the peak can be used as a reference point in calculating the overstride angle, or even serve as an approximation for the overstride angle itself. In order to prove or disprove this hypothesis, it became necessary to expand beyond one subject, and to test across different strike patterns and levels of overstride, as well as with various subjects. The results of these tests will show that the peak of the shank angle cycle can in fact be used as a reference in determining overstride, but that additional corrections must be made depending on the runner. However, these corrections are relatively predictable, can be made systematically, and are overall small in magnitude.

5.3 Testing with different levels of overstride

In order to test the system across different levels of overstride, a subject was subjected for her ability to control her level of overstride by changing her strike pattern. The subject naturally overstrides very little, landing with a clear forefoot strike directly under the knee as shown in Figure 18a. By transitioning to a rearfoot strike, the subject naturally increased her overstride to land more comfortably, as shown in Figure 18b. By exaggerating her RFS, the subject extended her leg even further in front to emphasize landing on the heels, and as a result continued to increased her overstride, as shown in Figure 18c. Later tests showed that different strikes do not significantly affect the results of the system, so for the purpose of analyzing this test, it is reasonable to assume that the magnitude of overstride is the only thing changing across trials.
In these trials, the actual overstride angle, as determined by the shank angle at the time of initial contact, was compared to the peak of the shank angle cycle. As the magnitude of overstride increases, the difference between the peak angle and the overstride increases as well. Figure 19 shows the comparison of the actual overstride angle with the peak angle, along with the line $y = x$, which represents where the peak angle equals the actual overstride angle. In the first trial, where the subject is running without overstride, the average residual between the peak angle and overstride angle, as defined by $(\text{actual overstride angle}) - (\text{peak angle})$, is -0.55°. In the second trial, as overstride increases to a range between 0° -4°, the average residual increases slightly in magnitude, to -0.59°. In the third trial, as the subject pushes herself to an increased overstride angle greater than 3°, the error increases to -2.37°.

Figure 18. Varying overstride levels. Subject is able to change her magnitude of overstride by changing her strike pattern from FFS to RFS. Note that the exaggerated RFS in 18(c) was very unnatural for the runner.
What this data tells us is that as the peak angle increases, the correction required from this peak angle value to get the overstride angle increases as well. This can be visually represented in Figure 20. As seen, as the peaks of the shank angle cycles increase in value, the differences between the overstride angle and peak angle also increase. The two angles are represented by the red and cyan dot respectively. The red line represents the portion of the force plate data that was used to determine initial contact.

In the trial without overstride, average residual between the peak angle and overstride angle is -0.55°. As overstriding increases, average residual increases very slightly to -0.59°. As the subject exaggerates overstride the error increases to -2.37°.
In order to quantify this correction and ensure this pattern is not subject-specific, studies with multiple subjects were conducted to confirm a pattern, which will be elaborated on in the following chapter. One important thing to note about this particular subject is that the corrections needed when she is reaching levels of higher overstride tend to be much larger than normal. This is because the subject found overstriding extremely unnatural, and consistent overstride was difficult for her to achieve. The subject ended up swinging her foot out to a distance further than she could comfortably land at, meaning she would pull her foot back slightly before contacting the ground. This was confirmed by visual analysis of high-speed video, and explains the bigger difference between the peak angle and the overstride angle at initial contact when she is exaggerating her overstride. In subjects who naturally have a higher overstride, the correction required at the same peak angles is much lower.

5.4 Conclusions from preliminary explorations

Overall, initial testing with the force plate shows that in cases where there is little to no overstride, the peak angle of the shank cycle serves as a reasonable approximation for the overstride angle, with residuals averaging about half a degree. As overstride increases, the peak angle could still be used as a reference point, but a correction needed to be made from this peak to determine the actual overstride angle. Based on a single subject who was able to achieve multiple levels of overstride, it appeared the correction may based on a weak linear relationship, where the correction increases along with the peak angle. However, more data was needed to determine whether or not this hypothesized correction would be appropriate, as well as to determine the extent of errors in this approach.
6 Additional Testing

6.1 Methods

In order to test the hypothesis of introducing a linear correction based on peak angle and to further develop the system, ten volunteer subjects were studied under the same lab conditions. The subject group included 4 females and 6 males (age, 23.4 ± 5.01 years; height, 171.41 ± 9.25 cm; mass, 68.76 ± 13.7 kg) with a mix of strike patterns (4 FFS, 6 RFS). There was a wide range in running frequency, ranging from 0 miles per week to 30. Five subjects self-classified themselves as runners (10+ miles a week), and four self-classified as non-serious runners (0-10 miles a week). One subject used to be a runner but was recovering from injury. Because of the diversity among subjects, there was a relatively wide range in overstride and form, making it an ideal test for validating the system across many types of runners. The testing protocol was approved by the Institutional Review Board at Harvard University, and subjects provided written informed consent in accordance with institutional policies.

Subjects were instructed to warm up for five minutes at their preferred speed, and then instructed to run for three 60-second trials at 2.5 mps, 3 mps, and 3.5 mps. The speeds were chosen to represent a comfortable jog, a medium run, and a brisker run respectively, roughly corresponding to a 10:30-min mile, 9:00-min mile, and a 7:40-min mile. In each trial, the subject wore both the IMU system and reflective markers for motion capture, and the IMU system was synched to motion capture system for comparison.
6.2. Data analysis

The goal of this test was to verify the hypothesis that the peak shank angle could be used as a reference to determine overstride, by expanding the data set and examining patterns across multiple subjects. For each trial, the subject was given approximately ten seconds to reach speed on the treadmill before data collection started. Ten steps from each data collection, Steps 30-40, were then examined. For each step, the overstride angle was plotted against the peak angle to examine the correction needed, as shown in Figure 21. The line y=x represents the situation where peak angle equals the overstride angle, and no correction is needed. Data from all subjects are included in the graph.

**Figure 21. Observed overstride angle vs. peak angle**

As observed, very little correction is required when the peak shank angle is less than 4°. On average the correction value is less than 0.5°. As peak angles increase beyond 4°, the corrections increase as well, up to a maximum correction of about 1.5°. While
1.5° error is not bad for the purposes of detecting overstride, meaning the peak angle could still serve as a rough approximation, the data was studied further to determine whether or not this error could be reduced.

In order to examine the data more in depth, the peak angle was determined for all steps recorded in a trial, and the corresponding correction from the peak angle to overstride angle was calculated. The mean peak angle for each 60-second trial was then plotted against the mean correction required. Because the data tended to be cyclic and consistent, the mean was a suitable approximation for this analysis. Figure 22 shows a comparison of these values, and aggregates data from all ten subjects at the three tested speeds. As seen, there is only a weak linear relationship between mean peak angle and correction. This is not surprising, as every runner runs slightly differently, and gait patterns varying by a few degrees are to be expected. However, the important thing to note about this analysis is that the correction required is consistently less than a degree, regardless of peak shank angle, running speed, and strike type.

![Corrections Required vs. Peak Angles](image)

**Figure 22.** Mean values for corrections required vs. peak angles. Though the linear relationship is week, all corrections required are less than 1 degree.
Though the linear relationship is extremely weak, it could still be applied to the algorithm for detecting overstride angle to minimize the magnitude of the error by a non-trivial amount. The reason for this is because all corrections are negative, meaning the overstride angle is always slightly smaller than the peak angle. This makes mathematical sense because the peak value will always be the highest value, and is also consistent with what was visually observed earlier. By estimating a correction with an equation with a negative y-intercept and subtracting it from the peak value, we can minimize the absolute value of error between the actual overstride angle to the value we predict.

The overstride detection method was then updated to include a correction from the peak angle to determine the overstride angle. A summary of the final process is shown in Figure 23.
Figure 23. Summary of updated process to detect overstride. The overstride angle detection method is highlighted in the green box.
The updated method was applied to the dataset consisting of Steps 30-40 for the ten subjects. With the correction introduced, the mean error from the predicted overstride value to the actual overstride value was determined to be $0.08° \pm 0.32°$, which is without a doubt sufficiently low enough to measure overstride. A plot of the observed vs. predicted results are shown below in Figure 24.

**Figure 24. Observed vs. predicted overstride values**

The results of this testing show that even though there is only a weak relationship between peak angle and the correction required from the peak angle to determine overstride, using this relationship to add in a correction still makes a difference. The
magnitude of the correction required as small enough such that it does not significantly matter if the estimation is not exact. As previously observed, the average correction required across any subject is less than 1°, meaning if one simply approximates the peak angle as the overstride angle, the error would likely be less than a degree, and any correction you make would also not be off by more than a 1°, provided the correction does not exceed 1°. By adding in the correction derived from empirical methods, we were able diminish this error further, to 0.08° ± 0.32°, verifying that this method of determining overstride would be suitable for measuring overstride.

As part of a final evaluation, the system was evaluated against the original design requirements from Chapter 2.

The primary goal of the proposed system was to offer a wearable solution to measure overstride, with an accuracy of ± 3°. We saw that the IMU system making a uniaxial approximation in the sagittal plane was able to measure the shank angle relatively accurately compared to the Qualisys motion capture system, with an overall mean average error of 3.97° which is reduced to 1.5° around the area of interest. By using the peak shank angle as a reference point and making the appropriate correction, the overstride angle can be estimated with a mean average error of 0.08°.

One limitation to the accuracy of the system occurs at higher speeds, and lies with the relatively low-cost Razor IMU that was selected. At running speeds around 3.5 mps, the data starts to waver with a low frequency, which can be filtered out in post-processing to yield more accurate results, but which is difficult to account for in real-time. This is likely due to the gyroscope bias error, which has a random walk component independent of the stationary bias.\textsuperscript{39} Though the stationary bias was accounted for in the designed
system, the random walk component was harder to calibrate out, despite the inclusion of the DCM matrix. Future work should include improving the sensor fusion algorithms, or investigation into a higher-end industrial grade sensor. More information on the wavering data can be found in the Appendix.

Outside of accuracy at higher speeds, the system achieves the other stated design requirements. By using an IMU sensor system attached to the body via a compression sleeve around the tibia, the system avoid exerting forces across any moving joints, and does not interfere with the regular biomechanics of running. The system is completely wearable, weighing 135 grams, or 4.76 ounces.

Despite its lightweight profile, the compression sleeve attachment is sturdy enough to minimize sensor accuracy over time, resulting in little to no significant movement over the course of a 10-minute high speed run, which included deliberate leg shaking.

The system is also able to process data at a rate of 27 Hz, which was sufficient for the purpose of measuring overstride in this project, though future work could look into improving this value, perhaps by doing more of the processing on the microcontroller instead of on the IMU.

Lastly, the system functions successfully for all types of subjects, and is able to reasonably measure overstride angles for both RFS and FFS runners, regardless of their level of overstride.
8 Conclusion

The main goal of the project was to prove that a simple, wearable system could be a successful alternative to existing gait retraining methods for reducing overstride. By designing a system using IMU technology and verifying the concept through extensive testing, it was shown that a single, strategically-placed sensor coupled with a microcontroller has the capability of replacing treadmills and running coaches, and could revolutionize the way gait retraining is conducted. This system offers a low-cost opportunity for everyday runners to monitor their gait and improve their form in a way that could help reduce the risk of injury.

The implications of this project expand beyond individual runners as well. The introduction of a portable tool that can monitor gait will allow biomechanical research to expand beyond lab conditions, where the running environments are often artificial, and into more natural running environments. Long-term studies can be conducted more easily, as subjects are able to collect data independently outside of scheduled lab times. Additional metrics such as cadence (steps/minute) and impact (force at which the runner hits the ground) can be added into the system using the IMU data, offering even more information for runners and researchers alike.

Overall, further developing this project will help contribute to the smart fitness movement, as everyday athletes continue to strive towards to quantification of performance and data-based training. With the assistance of devices such as this one, it is hoped that one day we will be able to fully understand and adjust our movements in a way that not only maximizes performance, but also simultaneously reduces harm.
APPENDIX A: Synchronization methods

In order to synch the IMU system with Qualisys motion capture, a BNC cable was modified to hook up to an Arduino. One wire was soldered to the central conductor, which was connected to Pin 22 of the Arduino. Another wire was soldered to the braided shield, which connected to the Arduino’s ground. The BNC connector was then connected directly to the Qualisys A/D board.

Once the IMU system started collecting data, a 3-second start pulse was sent to Qualisys, which collected the pulse in one of its analog channels. At the beginning of the next 1-second pulse, the Arduino started collecting data. Using these pulses, it was possible to synchronize the data in post processing, and shift the time-stamps so both data collections “start” at 0 seconds. Only the long pulse and the first short pulse are needed to synchronize the system. However, periodic pulses were introduced to serve as checks that the synching method did not degrade over time. There were no cases where synchronization degraded over time. After multiple trials, the 1-second pulses were eliminated from the final code.
To verify this synch method was valid, a test was conducted where the IMU was secured to a yardstick, which was then subject to sudden, sharp, controlled movements from a stationary position. This motion was simultaneously captured with Qualisys and the two data sets were synched. As shown below, there are no significant time delays with this synch method.
APPENDIX B: Acceleration data

Because the Razor IMU has built in accelerometer, the idea of using acceleration to detect initial contact was originally considered. The acceleration data was studied against force plate data to determine if there were any patterns around initial contact. It was noticed that by filtering the acceleration data slightly with a SMA of span 3, hints of patterns started to emerge. However, the sample rate of 27 Hz was too low to see clear patterns. To measure impact, something above 100 Hz would be much more suitable. Because the patterns around shank angles were sufficient to measure overstride, the accelerometer was not used in this project. Future work could include a sensor with a higher sampling rate that could use the acceleration data to confirm initial contact, or to offer information on another running metric, such as impact.
APPENDIX C: Razor 9DOF Limitations

At speeds around 3.5 mps, the Razor occasionally wavers, as shown, in a way that is difficult to predict. Normally, the angles should be centered around -90 (perpendicular to the ground), which is then shifted to 0. Though the data is wavering, the magnitude (peak-trough) of the data being read is correct.

It is shown that a high pass filter can eliminate the wavering, implying that there is some low frequency noise that is interfering with the readings of the IMU. While straightforward in post-processing, this is difficult to achieve in live-time. Future work should investigate ways to correct for this noise, either with more powerful sensor or improving the filtering algorithms.
APPENDIX D: Arduino Code

#include <string.h>
#include <Scheduler.h>

int inByte = 0;
char Str1[50];
int idx = 0;

float currentPeak = 0;
float sensorValue = 0;
float peakValue = -150;
float threshold = -120; // set your own value based on your sensors
float Time = 0;
float offsetError = 0; // check to make sure the IMU doesn't have an offset (usually very accurate)
float angleOffset = 90 - offsetError; // set coordinates by shifting IMU reading from -90 (vertical) to 0
float currentPeak_adjusted = 0;
float peak1 = 0; // for the five data point window
float peak2 = 0;
float peak3 = 0;
float peak4 = 0;
float peak5 = 0;

int modOverstrideThresh = 7; // set the threshold from moderate overstride to overstride

int pinBNC = 22; // digital pin 22 for A/D board wiring through BNC
int pinLEDred = 51; // digital pin 51 for red LED
int pinLEDyellow = 47; // digital pin 47 for yellow LED
int pinLEDgreen = 43; // digital pin for green LED

int BNCstate = LOW; // ledState used to set the BNC

float roll, pitch, yaw;
char * p;
float xAccel, yAccel, zAccel;

long interval = 32; // interval at which to blink (milliseconds)
long previousMillis = 0; // will store last time data was requested
unsigned long currentMillis = 0;

void setup()
{

pinMode(pinBNC, OUTPUT); // digital pin for BNC connection
pinMode(pinLEDred, OUTPUT); // digital pin for LED
pinMode(pinLEDyellow, OUTPUT); // digital pin for LED
pinMode(pinLEDgreen, OUTPUT); // digital pin for LED

digitalWrite(pinLEDred, HIGH); // check LEDs
digitalWrite(pinLEDyellow, HIGH);
digitalWrite(pinLEDgreen, HIGH);
delay(1000);
digitalWrite(pinLEDred, LOW);
digitalWrite(pinLEDyellow, LOW);
digitalWrite(pinLEDgreen, LOW);

digitalWrite(pinBNC, HIGH); // send start signal to Qualisys
delay(3000); // signal lasts 3 seconds
digitalWrite(pinBNC, LOW);
delay(1000); // delay 1 second before starting data collection

Serial.begin(57600);
Serial2.begin(57600);

Serial2.write("#ot"); // Output angles in TEXT format, like ";YPR=-142.28, 5.38,33.52"
Serial2.write("#o0"); // Disables continuous streaming output of IMU

Scheduler.startLoop(loop2); // signal start of second loop which synchs and calculates

}

void loop()
{
currentMillis = millis();

if (currentMillis - previousMillis > interval)
{
    previousMillis = currentMillis;

    Serial2.write("#f"); // Request one output frame from IMU connected to TX2/RX2.
    idx = 0;
inByte = 0;

    while (Serial2.available()) // Checks when serial port is ready to transmit data.
    {
        inByte = Serial2.read(); // Read data from IMU. Store in an integer variable
        Str1[idx] = char(inByte);
        idx++;
    }

    p = strtok(Str1, ",YPR=,"");
    roll = atof(p);

    p = strtok(NULL, ",");    
    pitch = atof(p);

    p = strtok(NULL, "," );
    yaw = atof(p);

    p = strtok(NULL, "," );
    xAccel = atof(p);

    p = strtok(NULL, "," );
    yAccel = atof(p);
void loop2() {

digitalWrite(pinBNC, HIGH); // turn the LED on (HIGH is the voltage level), which indicates the loops have started (synching purpose)
delay(1);

if ((sensorValue > -150) && (sensorValue < -15)) {

}  

if (sensorValue > peakValue) {
    peakValue = sensorValue;
}

if (sensorValue <= threshold) {
    if (peakValue > threshold) {
        currentPeak = peakValue;

        currentPeak_adjusted = currentPeak + angleOffset;
        currentPeak_adjusted = currentPeak_adjusted + (-.0235*currentPeak_adjusted -0.2599) // empirical relationship

        if (currentPeak_adjusted > modOverstrideThresh) {
            peak1 = peak2;
            peak2 = peak3;
            peak3 = peak4;
            peak4 = peak5;

        }
    }
}
}

p = strtok(NULL, ",");
zAccel = atof(p);

Time = millis(); // comment or uncomment depending on if you want to print the data
Serial.print(Time / 1000, 3);
Serial.print("");
Serial.print(roll);
Serial.print("");
Serial.print(pitch);
Serial.print("");
Serial.print(yaw);
Serial.print("");
Serial.print(xAccel);
Serial.print("");
Serial.print(yAccel);
Serial.print("");
Serial.println(zAccel);

sensorValue = yaw; // relevant shank angle
}
peak5 = 1;
}

else if ((currentPeak_adjusted <= modOverstrideThresh) && (currentPeak_adjusted > 20))
{
    peak1 = peak2;
    peak2 = peak3;
    peak3 = peak4;
    peak4 = peak5;
    peak5 = 0;
}

else if (currentPeak_adjusted <= 20)
{
    peak1 = peak2;
    peak2 = peak3;
    peak3 = peak4;
    peak4 = peak5;
    peak5 = -1;
}

// control LEDs on overstride behavior over the last five steps

if (peak1 + peak2 + peak3 + peak4 + peak5 < -2)
{
    digitalWrite(pinLEDgreen, HIGH);
    digitalWrite(pinLEDred, LOW);
    digitalWrite(pinLEDyellow, LOW);
}

else if ((peak1 + peak2 + peak3 + peak4 + peak5 >= -2) && (peak1 + peak2 + peak3 + peak4 + peak5 < 2))
{
    digitalWrite(pinLEDyellow, HIGH);
    digitalWrite(pinLEDgreen, LOW);
    digitalWrite(pinLEDred, LOW);
}

else if (peak1 + peak2 + peak3 + peak4 + peak5 >= 2)
{
    digitalWrite(pinLEDred, HIGH);
    digitalWrite(pinLEDyellow, LOW);
    digitalWrite(pinLEDgreen, LOW);
}

References


Friedman, Jason. “Introduction to human movement analysis.” Macquarie University. 15 October 2010


Additional image references:
