Apparel Concept Design for Analysing Range of Motion at the Hip to Prevent Injury

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Abstract: Range of Motion (RoM) testing can identify the underlying causes of an athlete's pain at the hip, be it muscular (extra-articular) or damage to the joint itself (intra-articular). The purpose of this study was to design a device which could detect characteristics of hip injuries from the motions and forces applied to the joint. Hence supplying a coach with a method to analyse and diagnose injuries in real time. A design to measure the RoM and gait at the hip was developed and later manufactured for testing on recreational athletes. Findings supported the device in its potential to identify gait events and competitive motion at the hip, despite the accuracy measuring less than that of the two-degree accuracy of the goniometer, competitive performance analysis within the study is evidence of a conceptual design. With development, apparel such as ours has the potential to supplement a coach's quantitative analysis, identifying responsible motions and performance metrics at hip responsible for injuries at the joint and the lower limbs using correlative data between motion and the onset of injuries.

1 INTRODUCTION

The hip joint plays a central role in an athlete's performance across many sports, however, its condition is often overlooked. In a study into collegiate athlete hip and groin injuries, Kerbel et al. (2018) found the hip to be a common location of injury, accounting for 6% of all athletic injuries. Because the synovial joint at the hip assists in all movement below the waist, it is subject to some of the most intensive demands of the body during exercise. As a result, damage to the hip can risk an athlete's performance, or their career.

Mcgurran (2017) depicts how athletes find their self-worth derived from their performance, and how they would tend to endure the immediate pain of injury, ignoring many serious injuries, particularly at the hip, for substantial periods of time. With a majority of hip injuries originating during adolecence Siebenrock et al. (2011) suggests young high-level athletes increase their risk of injury when subjecting the hip to repeated high stresses and directional loading while the skeleton is still developing.

An athlete's fear of injury has shaped training programmes to strengthen and protect the most vulnerable areas on the body. Consequently attempting to prevent injuries, fitness evaluations have become common practice in all sports from a young age, as coaches seek to identify potential areas of weakness. Relevent theory is based upon correlations identified between physical chara-cteristics and performance, for example, poor flexibility. Noonan and Garrett (1999) describe how a 'weak, stiff' muscle will significantly inhibit its energy-absorbing capabilities, increasing its susceptibility to strain injury. These fitness evaluation tests however are not discipline specific and are not always reflective of an unpredictable competitive scenario.

In the event of an injury whilst competing, evaluation is performed retrospectively, this becomes an issue when related to the hip and lower limbs. Misdiagnosis, due to the complex composition of the hip and lower limbs, has become extremely common. To better our understanding of the capability/ demands of the body, there has been an increase in performance monitoring technology, identifying patterns and trends for a coaches interpretation.

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Although vitals can be measured with relative ease, the physical demands on the joints, particularly at the hip, remain in the realm of theory. Consulting with Williams (2018) for his expertise on lower extremity injuries, he stated that there was no way to measure RoM at the hip in a competitive scenario. Such information would prove insightful for a coach's consideration in preparing an athletes training, to best prepare the athletes body for the demands they face in competition. Clearly, the analysis of the RoM has the potential to aid in the diagnosis of intra/extra-articular injuries and performance analysis of the hip. Supporting an athlete's pursuit of greater performance and reduced absence time due to injury.

2 LITERATURE REVIEW

2.1 Athletes' Approach to Hip Injuries

After a single week of inactivity an athlete can begin to experience muscular atrophy, and with an anticipated 6-8 week break in the event of a serious hip injury, these are feared amongst athletes due to the potential career setbacks.

In the analysis of injuries, it is unreliable to use anecdotal reports to indicate injury patterns, because of the number of external risk factors which may influence an injury mechanism. Whilst in more detailed studies additional independent factors can be considered, initial consideration begins with the broader picture of incidence rates, requiring a definite distinction between competitive and training scenarios. Although the two at times may overlap, they require different demands which can influence the likelihood of injury. Hootman et al. (2007) investigated over one million young athletes between 1988 and 2004 covering a range of sports. The findings support the premise that competitive situations exhibit a greater risk of injury.

There remains no universally adopted definitions for classifying injuries in competitive scenarios, typically varying in classification by the depth and focus of study. For example, in papers such as Cloke et al. (2010), 'non-contact' refers to an athlete's injury mechanism when an opponent is not physically interfering with play.

2.2 Musculoskeletal Analysis of Hip Injuries

Most hip injuries share overlapping symptoms, often resulting in a vague diagnoses in the absence of an experienced professional. As such the design should be able to assist in supporting a clinical diagnosis of a hip injury and identification of the onset of symptoms.

The Kerbel et al. (2018) study into the epidemiology of hip and groin injuries, reports muscular injuries as the most common. Whilst this may be the case, the more severe injuries are intra-articular, with damage or deformities to the skeletal system carrying a longer absence. These are the more feared injuries at the hip. They explain that intra-articular injuries only become symptomatic after a significant period, leaving substantial damage in their wake. Intra-articular injuries often require surgery to rectify and achieve a timely return to participation. Thus, research conducted in the early identification of correlations of intra-articular injuries is becoming highly valued.

If properly utilized, simple tests such as identifying the RoM of the hip can narrow the list of possible injuries. For example, the Siebenrock et al. (2011) investigation into femoroacetabular impingement in adolescents, uses the premise that a decreased internal rotation indicates a 'structural abnormality' as the underlying cause. RoM testing however not limited to the identification of intra-articular injuries. Neumann (2010) describes how reduced motions at the hip might suggest damage to those muscles responsible however, the composition of the muscles in the region of the hip make identifying a single damaged muscle difficult. Byrd (2007) claims that differencing the onset of pain between active and passive motion of the hip can identify the intra/extra-articular nature of the injury. Should the injury be extra-articular, specific motions of the hip can be used to further narrow down the nature of the injury.

2.3 Clinical Measurement of the Hip

Manual handheld goniometry is both a low cost and simple procedure, making measurements highly accessible and easy for physiotherapy clinics. Yet, it is suggested that inaccuracies in the traditional method of measuring the hip's RoM remain, making hip injuries difficult to correlate and compare. (Yazdifar et al., 2013). Here, repeatability errors in traditional methods, compared with more contemporary video tracking methods have been reported. Still neither method allows for an easy method of performance comparison between athletes.

Elson and Aspinall (2008) identify the 'neutral' position of the pelvis additionally to be a key issue. Claiming that when lying prone, the posture of the pelvis is altered with respect to its position to the couch plane. Because both the pelvis and femur can move relative to one another it is imperative that measurement of the positional relation of both in a competitive scenario is taken.

2.4 Technology of Performance Data Acquisition

Fahrenberg (1997) suggests that the use of a piezoresistive accelerometer could help to distinguish between the postures and motions of test subjects, and ultimately, he concludes that such an approach is viable. However, he notes that the lack of any universal standardized guidelines for the positioning of such sensors prevents cross-laboratory comparisons between athletes.

Analysis of the human walking/running pattern in phases can directly identify the functional significance of the different motions generated at the individual joints. Tao (2012) explains this in the breakdown of the eight stages in a walking pattern, as the sequential motion completes three tasks; ‘weight acceptance, single limb support and limb advancement’. It is suggested that gait phases may each be detected by identifying the orientations of the leg segments at any one time, with the use of angular rate data derived from a gyroscopic sensor. Meaning our design should be capable of identifying the stages and characteristics of the individual’s gait cycle so that together with the RoM data and force readings sound conclusions may be drawn as to the motion of the lower body in high velocity competitive scenarios. This data then paired with additional external analysis could help to build a better understanding of the demands of the lower limbs performing certain motions.

3 DESIGN

3.1 Femur Movement

The design proposed and discussed herein uses an accelerometer to measure the RoM at the hip. In the same way the RoM measures femur rotation away from a midline designated from an initial stationary stance, an accelerometer can measure the independent inclination of each axis away from its initial position. By attaching an accelerometer to the upper leg, it is expected that the angle through which the leg turns and hence the angle through which the femur rotates within the acetabulum may be measured. This accelerometer may, thus, measuring flexion, extension, internal and external rotation as well as abduction and adduction.

Concerning the selection of a sensor for the design, an accelerometer was deemed most suitable. Firstly because of its linear relationship with changing temperature. The minimal linear acceleration and zero-g deviation sensitivity of the sensor when under varying temperatures, suggests a change in body temperature, due to muscle exertion or change in environment will minimally impact our data accuracy in comparison to other sensors.

A smaller power supply would also be beneficial for the design, reducing unnecessary weight and hence reducing the likelihood that the design may interfere with the performance of the athlete. The power consumption of the accelerometer is significantly lower than its counterparts, making it the favoured sensor to minimize the power supply in the design.

Furthermore, noting all sensors are subject to unwanted influence imbedded in the device’s nature. The raw accelerometer data is also likely to suffer from noise due to mechanical vibrations and calibration errors. However, accelerometer errors do not diverge with time and can be handled effectively; a stark contrast to a gyroscope which when subject to sudden movement will result in large drift errors. Because of the capability to constructively handle the errors which may arise from accelerometers, the design of a sole accelerometer inertial measurement unit would seem most promising for the design.

Alongside the exact orientation of the accelerometer, the ability to determine what phase of the gait cycle the hip is in, such as whether the leg is planted or free, will aid in our understanding of motion at the hip. This understanding can be achieved using the vertical acceleration profile measured by the accelerometer.

Further important considerations relate the frequency domain characteristics of the accelerometer, and associated data collection hardware and software. It is necessary to tailor the dynamics of the measurement system to extract accurate, meaningful data, whilst rejecting sources of noise and ensuring aliasing is not a factor. Seeing to at least match the accuracy of a goniometer the system must be capable of measuring a Minimal Detectable Change (MDC) of at least 2^{0} . It is noted that many previous studies such as Turcot et al. (2008), used sensors with a sampling rate of 100Hz and this can be deemed the minimum requirement for the sensor to begin testing.

3.2 Sensor Location

For the location of the sensor on the upper leg, it was important to locate the sensor in a position where it will experience minimal movement because of muscle contractions during dynamic motion. This is to be found along the anterior of the upper leg on the Vastus Lateralis as described by Backhouse (No date). Tong and Granat (1999) noted that provided the sensor remains along the line of the landmarks the sensor reading will be replicable (Figure 1), and hence independent of the user. Potentially initiating a standardised methodological approach for cross-comparison experiments. For ease of positioning, the sensor will be located at the lower end of the upper leg towards the knee, and in line with the Lateral Epicondyle, thus following the clinical positioning of the goniometer. Similar to that of Turcot's (2008) experimental positioning when investigating Osteoarthritis patients.

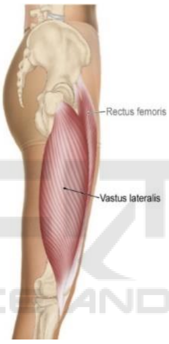

Figure 1: Vastus Lateralis in the Sagittal Plane and the Dotted Line indicating where Tong and Granet (1999) suggests the same experimental data from the accelerometer is obtained. (Muscolino 2018).

3.3 Pelvic Movement

In the same way that the femur moves from its datum, so too will the pelvis from its datum (Elson and Aspinall, 2008), particularly in vigorous dynamic motion. The pelvis has a natural inclination known as pelvic tilt that needs to be measured statically prior to dynamic measurements, and accounted for in subsequent processing. However, pelvic tilt in the sagittal plane can be determined by measuring the angle between a line intersecting the ASIS and PSIS landmarks, and the horizontal (Transverse) plane. Whilst, in the Coronal Plane, a line between the two ASIS landmarks across the pelvis, compared to the transverse plane indicates the natural pelvic tilt. Measuring the rotation of the pelvis using the change in inclination of the gravity vector from its initial stationary reading will yield the change in pelvic angle relative to all three-axes, allowing for full 360-degree monitoring of the pelvis. Because of the compression shorts ability to secure the sensor close to the skin, an additional accelerometer located between the PSIS landmarks on the back will minimise the adverse effects on performance, locating the sensor weight close to the centre of gravity of the human body, least influencing performance.

3.4 Gait Analysis

Although not the focus of this study, accelerometers can measure a range of performance metrics. The likes of gait metrics (e.g. cadence, stride length and forces through the leg) can complement the RoM data, indicating the position of the leg and weight distribution through the stride and across the lower body, as indicated by research such as Turcot et al. (2008). In addition, future developments may see the range of recording metrics expand further with the growing capabilities to interpret the recorded data.

3.5 Accelerometer

The accelerometer used is the Adafruit MMA8451 breakout. Its relatively small size facilitates the sensors' positioning for concept evaluation. The Adafruit supported Arduino software is readily adaptable to the manipulation of the sensor readings for exporting in a convenient format. The time-stamp of each reading will be marked in milliseconds due to the 9.6kHz sensor refresh rate, later being converted to a more traditional unit. For concept evaluation, an SD card was used to record the delimited data and provide a means of importing the data into Matlab for processing.

4 METHODOLOGY

4.1 Participants

Prospective athletes were contacted and given an information letter outlining the investigation's aims, testing protocol and hence the requirements of their participation. Recreational athletes participating in Football, American Football and Running participated in the testing, and provided informed written consent prior to testing and also completed a brief survey to determine limb dominance and suitability screening. Screening criteria for participants included:

- No previous serious hip injury or defect known within the last 12 weeks so not to indicate significant injury
- Injury-free status at the time of testing (Absence from training for no more than the preceding three weeks, currently full participation in training and/or not recovering from participation in vigorous exercise performed prior to testing.)
- Remained injury free for the duration of the testing

Screening criteria was performed to ensure healthy participants in order to capture data under conditions of full uninhibited performance. All participants met these criteria. Participants were asked to supply their own sportswear to wear over the shorts to create a traditional environment for regular performance analysis. The footwear of each participant were also recorded because of their capacity to affect the elasticity of the forefoot region, changing contact time and propulsive force with intensity.

4.2 Study Overview

RoM testing was performed in accordance with the clinical specifications after participants performed a warm up of their choosing with which they are familiar and comfortable. Participants were individually examined over a period of three days and underwent dynamic testing individually. A total of three participants were selected (3 Male) (age = 24.3 ± 3.39 years, stature = 181.19 ± 7.62 cm, mass = 78.167 ± 6.8 kg, Body Mass Index (BMI): 24.45 ± 2.3 kg/m^2) as this was deemed a suitable sample size for proof of concept.

4.3 Testing Protocol

Participants wore instrumented compression shorts in a size which they personally deemed comfortable, and were adjusted so the midline of the elasticated waist band aligned with the ASIS and PSIS landmarks. These landmarks, as well as the greater trochanter and lateral epicondyle midline, were also scribed with a marker pen on the outside of the compression shorts for reference. The shorts were then returned for amending and stitching of the accelerometers in line with the reference markings. The accelerometers were stitched securely in position and the control unit (Arduino) was secured between the PSIS landmarks for dynamic testing by securing the unit to an adjustable GoPro strap.

4.4 Procedure

The same pair of running shoes were worn by each participant for all tests, preventing changes in limb kinematic data during running and running economy. All participants wore low rise running shorts to avoid interference with the sensors above the compression shorts. Tests were conducted indoors so that the environmental conditions varied minimally. Running surface conditions were dry and clear of interfering debris. Accelerometers were calibrated prior to fitting on the participants.

4.5 Anthropometric Data

Factors such as body composition, anatomy and injury history can all predispose an athlete to risk of injury, consequently, basic anthropometric data was acquired prior to testing. Anthropometric data were taken in an isolated first aid room, preceding the RoM tests to correlate any plausible phenomena that may compromise the results. A wall mounted tape measure (GIMA 27335) and electronic scales (Etekcity 4074s) were used to measure stature and mass (±0.1cm and ±0.1kg respectively). The upper leg circumference was measured using a fabric tape measure around the point the accelerometer is attached ±1mm. The anthropometric data gathered here, was interpreted in excel to obtain averages and bounds for the participants.

4.6 Clinical RoM Testing

As discussed in section 2, the static RoM at the hip was measured using a goniometer (IDASS 12” Goniometer) to the nearest degree for the base reference readings. These were compared to the sensor readings to verify the accuracy in the design’s RoM measurements. An examination bench was used to perform the stationary RoM tests and care was taken to observe whether any soft tissue around the hip restricted the motion of the joint below its full range. Both dynamic and passive measurements were taken, once without the shorts on, and again with the shorts on, to provide a baseline the RoM readings. Participants were constantly spoken to throughout the tests to clearly define the requirements from the participant.

4.7 Treadmill – Gait Analysis

To compare the design's capability in measuring basic gait characteristics, treadmill (LifeFitness 9500HR) running at a constant pace was used. A 25 s run at a comfortable continuous pace was selected to replicate similar testing methods performed by Turcot (2008). The participants were given as much time as necessary to become accustomed to the pace before testing commenced. They were then required to walk for 30s before increasing the belt speed to their fastest comfortable pace. Sensor positions were checked before and after each repetition to ensure constant functionality and that they remained in line with the reference landmarks. The data collected here is used to analyse the subject's gait and compare with published results hence, validating the design's performance. This comparison will confirm a working model prior to the addition of further programmes of activity allowing the collection of further data. This validation comes in the form of the tracing of Y-Axis acceleration in Matlab and comparing the data to that of experiments conducted in similar research ventures of gait analysis. Participants were required to rest for two minutes between all repetitions.

4.8 Shuttle Runs – Isolated Change in Direction

As no identifiable research methods look to analyse the more dynamic performance metrics, testing began with one of the simpler movements. Performing 10x, 10m shuttle runs at a comfortable pace, looking to isolate a basic 180-degree turn. The 10m line was marked using electrical tape to prevent the participant slipping on any foreign object whilst performing. The data will be reviewed alongside frame by frame slow-motion footage for time references (120fps, GoPro Hero 5). The camera remained stationary throughout the entirety of the testing, although the participant's velocity caused them to occasionally turn outside of frame.

4.9 Illinois Agility Test – Unpredictable Hip Movement

This test looks to recreate the RoM in a more competitive scenario. Being initially unaware of the kind of data the sensors might capture; this test was more intended as a scope to the future developments of the design. The test can be found commonly performed as part of a fitness evaluation, measuring agility and so recreates a basic athletic scenario where the subject is competing against a stopwatch. The data is predicted to be noisy however, will give us our first insight into the type of data obtained in a competitive scenario.

4.10 Data Analysis

All data captured was run through Matlab Software, identifying the acceleration values for each axis and the subsequent inclination angles of the sensor and hence the femur and back orientations. The process of the Matlab software is as explained in the Design Section previously.

5 RESULTS

5.1 Gait Characteristics - Treadmill

Due to time restraints any filtering and manipulation of data was minimal. Only a moving average filter was applied due to its ease and ability to remove much of the unwarranted noise.

From processing the Y-Axis Acceleration, it is possible to visualise the gait cycle of each participant in each test. In the increase in acceleration of the treadmill, the consequential increase in stride length and intensity shows a visible increase. This observation was most noticeable in Participant 3's Y-Acceleration graph shown in Figure 2, by the sharp increase in amplitudes when the pace increased before and after the red line at 34s.

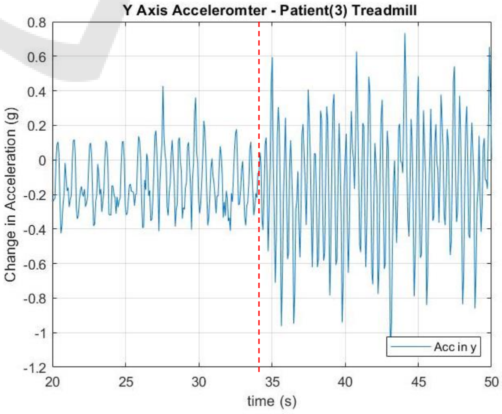

Figure 2: Participant 3 – Treadmill Leg Accelerometer - Y-Axis Acceleration Plot (5km/h ->> 9km/h).

The increased acceleration values indicate a greater force moving through the leg as the participant looks to increase his stride velocity and cadence to coincide with the belt's increased velocity from 5km/h to 9km/h.

Figure 3 presents a more detailed view of the participants running strides. Exhibiting the type of wave that would be expected prior to interpretation using 3rd party software for the analysis of further gait characteristics i.e. toe off, heel contact and cadence etc.

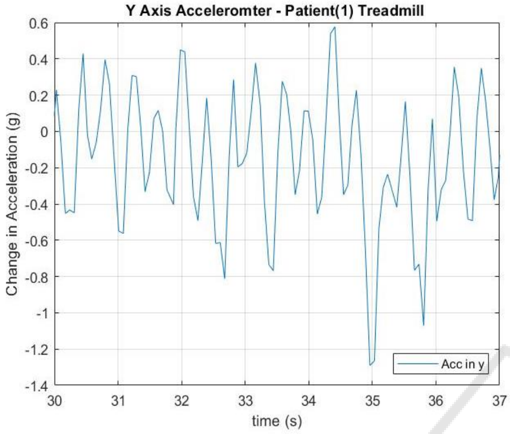

Figure 3: Participant 1 – Treadmill Leg Accelerometer - Y-Axis Acceleration Plot, Showing a zoomed in look at the stride pattern whilst at 9km/h.

5.2 Gait Characteristics – Shuttle Runs

Like the Treadmill Y-Acceleration graphs, it is possible to identify a stride pattern and external events, however the addition of the changing of the stride has made the interpretation of the data more difficult. Aligning the video with the data, shows each of the negative peaks to be the increased force experienced through the leg whilst changing direction, each of the 10 times shown in Figure 4.

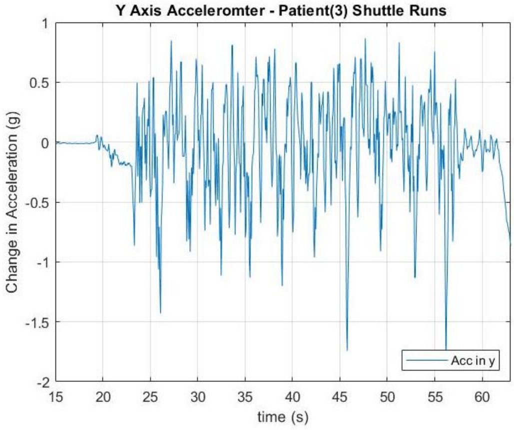

Figure 4: Participant 3 – Shuttle Run Leg Accelerometer - Y-Axis Acceleration Plot.

Participant 3 performed the test the fastest and exhibited more defined peaks when changing direction suggesting that the increased peak definition comes because of an increased force through the leg whilst changing direction, implying Participant 3 to be more agile than Participant's 1 and 2.

5.3 Gait Characteristics – Illinois Agility Test

The added change in direction with the agility test makes the data harder to interpret. Participant 3 completed the test fastest in 16.77s, and their resultant data makes for clear reading in Figure 5.

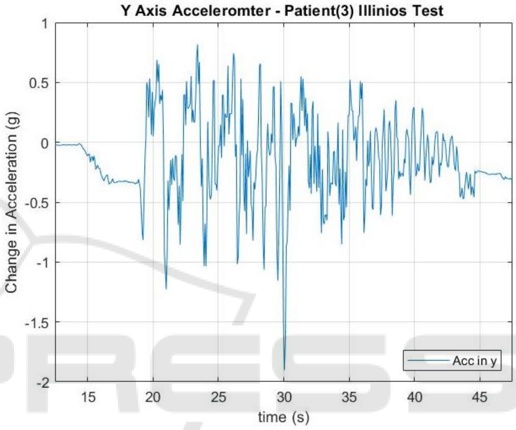

Figure 5: Participant 3 –Agility Test Leg Accelerometer - Y-Axis Acceleration Plot.

The decrease in stride length between the initial straights and corners when the participant decelerates, is signified by the increased frequency and lower negative acceleration peaks. Whilst the sharp positive peaks indicate a lengthen in stride as the participant drives the knee higher to accelerate as quickly as possible along the straights to gain speed.

5.4 RoM against Goniometer

Flexion and extension data proved promising for initial testing, carrying differences of 3.9º, -17.8º and -5.0º for each Participant respectively. The limit of maximum motion was held for an unspecified amount of time to allow a plateau to generate in the sensor data, enabling the angle of the hip to be clearly identified, as shown in participant 1's flexion measurement in figure 6.

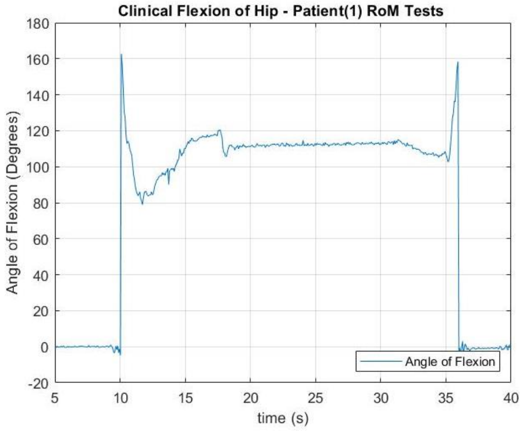

Figure 6: Participant 1 – Static Flexion of the Hip.

Contrastingly sagittal plane motion proved very poor. Examples of this came in the measurements of participants 2 and 3 abduction and adduction measurements (Figure 7).

The adduction measured from participant 3's data, exhibited a 33.00% difference from the goniometer measurement while abduction heralds a higher percentage difference of -57.00%. A high noise is also noteworthy in the data, which is believed to originate from the sensors high operating frequency when the individual holds an uncomfortable hip position at the maximum RoM limit resulting in the recording of minor oscillations as the body tenses so to hold the unnatural position.

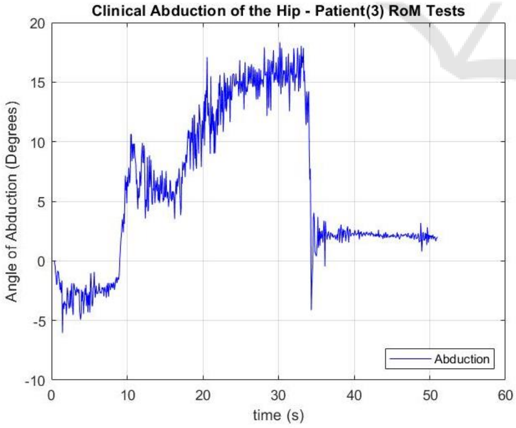

Figure 7: Participant 3 - Static Abduction the hip.

Internal and external rotation for participants 2 and 3 exhibited the same inconsistencies and inaccuracies. With participant 2's graphs (Figure 8) showing the plateau at angles greater than that measured for internal rotation (+22.86%), whilst external rotation seemed reasonably accurate (+15.625%) compared to other internal and external rotation measurements in comparison.

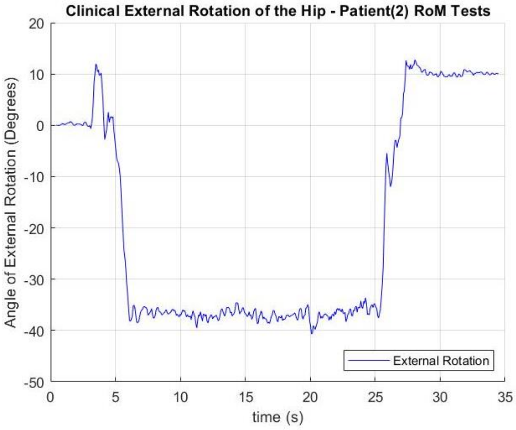

Figure 8: Participant 2 – Static External Rotation of the Hip.

5.5 Dynamic RoM Analysis

When performing dynamic tests, similar phenomena to that in the gait and static RoM measurements were identified. This is expected as the two naturally coincide. The treadmill elicited a repeating similar flexion and extension amplitude range for all three participants in accordance with their personal running form. The increase in velocity of the belt resulted in the participants consequently increasing their cadence and length of their stride to match the new velocity of the belt. Participant 3's data showed great definition on the treadmill as did their Y-Acceleration graph (Figure 9).

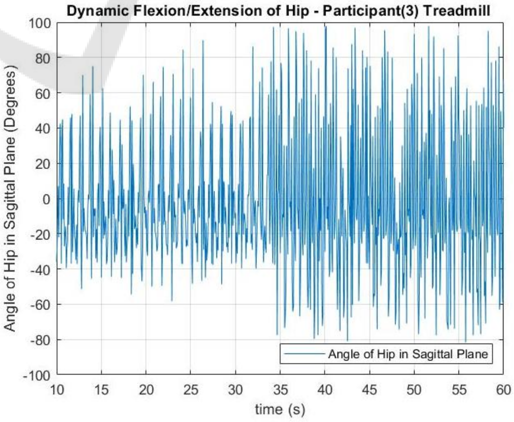

Figure 9: Participant 3 – Dynamic Flexion/Extension of the Hip - Treadmill (5km/h ->> 9km/h).

Conversely to participants 1 and 3, participant 2 exhibited an inconsistent stride pattern, resulting in occasional smaller amplitude breaks.

Abduction, adduction, internal and external rotation also exhibited the same inconsistent and inaccurate pattern as seen in the stationary measurements. Evidenced most from cartesian angle graphs. The data was far greater than that would be commonly expected for a consistent pattern of running, often peaking at values greater than 75 and 40 degrees for participants 1 and 2 respectively. These inaccuracies left the data gathered in these motions discounted from any further evaluation.

5.6 Dynamic Rom Analysis – Shuttle Runs & Illinois Agility Test

When concerning the free dynamic testing, flexion and extension data is very sharp and the peaks very defined. Instances of changing direction can be identified in the small periods of low amplitude in between the large peaks caused because of the athlete driving the knee forward to accelerate. This is evident in both the shuttle runs and agility graphs and is exhibited in Figure 10.

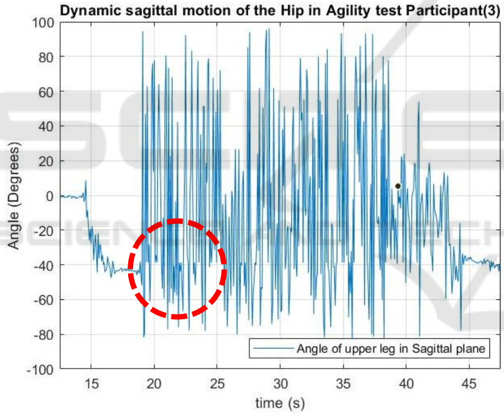

Figure 10: Participant 3 – Dynamic Flexion/Extension of the Hip – Agility Test. Red dotted circle signifies low hip angles when decelerating. This shape on the graph can be used to identify deceleration phases and to evaluate the actions of participant during testing.

The very sharp peaks and rapid changes in the angle of the hip are shown even more in the agility test data for that of participant 3. Again, the changes in direction can be seen in the smaller amplitude breaks however these are even smaller and harder to identify between the greater peaks and angles of the hip when the participant in driving their leg forward to accelerate as quickly as possible.

6 DISCUSSION

6.1 Reliability of Results

The sewing and tape holding the sensors in place held throughout testing, however the wiring to and from the sensor had the nature to snap when put through the more dynamic testing and so mid testing repairs were needed. Leaving it necessary to perform repeats as the wires would snap during the test. It was also noticeable that the back sensor stitched into the elastic waist band, remained stiff and upright, often losing skin contact when the participant surpassed an angle of approximately 30 degrees' flexion at the waist.

Environmental errors came from the Treadmill used, likely introducing errors between participants, due to them being open access to the public. Belt speed was unverified and so is likely not to be the exact velocity output read off the dashboard due to friction and wear in the machine. The dynamic tests also saw occasional slipping which was evident upon video review. The participants selected footwear, was not always the most suitable for indoor flooring and lacked the friction for a dynamic turn, which would affect sprint performance and the agility test times.

6.2 Gait Characteristics and Comparisons

The purpose of the treadmill testing phase was to first initially validate the sensor's capability to record basic acceleration data. In doing so, allowing us to evaluate and identify the stride phase the participant is in.

Comparing the shape of our graph to that of other gait analysis papers, a similar trend can be seen in the vertical acceleration throughout the running strides performed on the treadmill by the participants. The acceleration pattern exhibited walking over the initial 30s in Figure 2 is like that of Yang et al (2012) study, the repetitive similar amplitude peaks (+0.14g, -0.40g) showing the participant walking at a consistent pace. Figure 3, zooming in on the acceleration line for Participant 1, shows a sharp acceleration pattern from peak to peak (+0.38g, -0.41g), again like Yang's study. However, lacking the definition at the peaks to that of Takeda et al (2008) study. Unlike Takeda's data, the accelerations exhibit a single peak acceleration value, rather than a cluster of data points around the peak producing a subtle curve around maximum amplitude. This comes as a result of an aliasing effect. With the athletes performing movements at a rate greater than the sensor can capture. In increasing the sensor frequency to greater than 100hz it is believed that such aliasing would be avoided, in turn improving the resolution of the data. Less than 100Hz value being more suited to the slower gait analysis experiments conducted by the likes of Turcot et al. (2013), designed to analyse slower motions. Increasing our sampling frequency would provide us with additional data points at the peaks once filtered, leaving a more defined waveform, aiding in the identification gait events and action detection

Using these peak accelerations however, changes in running speed are identifiable, one such event is evident in the increase from 5km/h to 9km/h in Figure 2 for Participant 3, as the peaks increase to a consistent new amplitude. However, this can be used to analyse the movement of the athlete for more than single speed changes alone. Shown in the shuttle run graph in Figure 12, the smaller amplitude accelerations between the negative peaks signify the decrease in stride length, decelerating before changing direction 180 degrees. The sudden sharp peaks then signify the greater forces experienced by the sensor, as the athlete drives their knee forward after changing direction looking to accelerate into a sprint, heralding a greater force through the leg and up through the hip.

Despite the resolution difficulties, the vertical acceleration has allowed the identification of the gait phases. This is possible when a relatively consistent waveform is produced as the stride pattern remains consistent, like that of our participants running on the treadmill. However, in more dynamically demanding competitive scenarios these consistent peaks will not be observed (Figure 10), One example of such difficulties are the changes in peaks when participants performed repetitive dynamic actions like the turns in the shuttle runs, leading to suspected variations in participant intensity as they began to fatigue over time. Participant 3's shuttle runs shown in Figure 4 show lower peaks for turns eight and nine. It is suspected that their muscles exhibited a lower force to decelerate as they were running at a lower speed towards the end of the 10 shuttle runs. Additional testing, timing each length of the 10m sprint to measure intensity may verify this, and if found true can be used as an additional metric for a coach's consideration. However, the possibility remains that this data could give us an insight not yet achieved into competitive athletic performance.

6.3 RoM at the Hip

Static RoM at the hip yielded conflicting accuracies for the different motions at the hip. Flexion and extension measurements proved promising for an initial concept, having an average difference of -6.3º to that measured with the goniometer. A greater difference than that of the 2° MDC of the goniometer that design looks to match, showing the measurement method and interpretation still requires work. The differences also fluctuated between being greater than that measured and less than the goniometer, therefore eliminating a systematic error as the cause. A variance of -6.3º from the goniometer is far from the accuracy which is required in the evaluation of athletic performance. Ideally this would be as small as possible for accurate measurements to ensure reliable conclusions can be drawn. Should an athlete experience hyperextension of the hip joint for example, then the results must be able to show this, and to what degree has the hip joint over-extended. A decrease in error could come with an increase in the resolution of the data as discussed before.

It is possible that using a gyroscope in tandem with the accelerometer may allow other motions of the hip to be measured accurately. Abduction, adduction, internal and external rotation, having maximum percentage differences of -57.00% and +65.11% respectively for each motion pairing. These percentage differences in abduction, adduction, internal and external rotation result in the data being disregarded in any further processing due to their unreliability.

A gyroscope can be tasked with exclusively measuring the rotation of the hip in the coronal plane, measuring abduction and adduction. This is likely more accurate than the accelerometers single gravity vector being used to measure all three axis changes in angles respectively. The addition of an accelerometer here may also help account for the gyroscopic drift which may be experienced in the dynamic motions but will require testing and further development to evaluate its suitability.

However, it is the case that many papers focus on the flexion and extension of the hip in gait analysis alone. Alonge et al. (2014) graphically plots the flexion of the hip through their gait motions. Once the pace is increased to 9km/h for participant 3 (Figure 2) the angles reflect that more of Alonge's gait flexion and extension results, peaking consistently around 40 degrees. It is very noticeable however, the peaks greater than that of 80 degrees despite the use of a moving average filter. At a comfortable pace ideally, the stride pattern will remain consistent throughout.

However, as the participant relaxes throughout the duration of the run, they may move back down the belt of the treadmill and must move forward again. This motion requires a larger stride and greater flexion and extension of the hip reasoning these large peaks. The participants related this inconsistent pace to inexperience running on a treadmill.

Peak changes in flexion and extension enable us to understand the stage of each test the participant was in when conducting the shuttle and agility drills. The lower peaks suggest smaller and lighter steps associated with changing direction and speed in the shuttle runs, and this is evident in the breaks in the peak accelerations (Figure 4). This occurred prior to the larger peak flexion and extensions of the hip associated with driving the knee forward to accelerate quickly. This ability to sense a change in direction is also notable in the agility tests (e.g. figure 14), suggesting it may be possible to identify actions of the athlete in a competitive scenario and hence measure the performance metrics of the hip required to perform such a movement. Opening the area of competitive scenario research to identify performance metrics associated with actions performed in play, serving as an additional method of performance evaluation. Such as the likes of the capability of muscles about the hip to produce moments when shooting in football, associating muscular performance to speeds obtained by the ball in flight. However, this will take a substantial amount of time and case studies to support this hypothesis. As well as substantial number of case studies to support the correlation study of hip RoM and consequential injures.

7 CONCLUSIONS

It was hypothesised that the measurement of RoM and gait in a competitive scenario could identify the position, motion and force through the hips and legs prior to and at the time of injury. In doing so supporting the real time injury analysis and the diagnosis of injuries, by using motions at the hip and their correlated driving muscles to identify possible muscle damage and causes of pain and injury.

Both extra and intra articular injuries can be identified by a change in the RoM at the hip. However, large differences (-6.3º) in the sensor's readings, means that sound conclusions drawn as to the exact angular position of the hip joint cannot be made. However, it is possible to visualise the motion of the upper leg. In cross examining video references to the captured data, it is possible to identify characteristics of an athlete's form which may impact performance. One such possible identification is from the force measured through the leg in figure 10. Showcasing participant 3's fatigue over time with lower peaks for turns eight and nine. Suspecting that their muscles exhibited a lower force to decelerate as they ran at a lower speed towards the end of the 10 repetitions. Such an example is relatively basic however, showcases the desired foundations of analysis of form and hip motion.

In testing on recreational athletes, it was possible to differentiate form and gait characteristics in a competitive scenario, unlike motion capture, giving a closer insight into the demands of the lower limbs. One such obvious example was the comparison of an athlete's acceleration and deceleration patterns. Increased driving angle (Figure 10), cadence (Figure 5) and the forces exerted through the leg (Figure 5), build a picture of the competitive performance of the athletes. Whilst testing in this research is limited, the findings are encouraging to show that a more detailed analysis of the hip and the lower limbs is possible when using our design. The shorts considerable lower pricing point and ease of use make the design more accessible to the general athletic market, laying the foundations to better our understanding of the competitive demands of the hip and lower limbs.

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