Locating Positions for Measuring a Golf Swing with Inertial Measurement Units: A Pilot Study

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***Abstract*—Golfers often face challenges in refining their swings, seeking cost-effective ways to enhance their techniques. Traditional coaching methods are costly and since they rely on the human eye, these techniques often miss important golf swing movements owing to the rapid pace of a golf swing. To address this shortcoming, an investigation into the potential of IMU sensors for the mapping of golf swings to aid both instructors and golfers was undertaken. Focusing on the leading shoulder's horizontal position relative to the club head, the study addresses two questions: determining whether IMUs can map a golf swing as well as determining the minimum IMU sensors required to track a golf swing. Thus, the goal of this pilot study was to identify if there are optimal placements for IMUs on the body. The premise is that by performing a consistent golf swing, golfers could improve their handicap. Thus, by tracking and visually displaying the phases of the golf swing, such data could aid in increased golf swing consistency by analysing not only the phases of the golf swing, but also the bodily movements.**

This pilot study relied on six participants who each repeatedly performed golf swings. IMUs were positioned in eight positions around the body from ankle to shoulder and several trials were conducted for each position. The results showed that IMUs were useful in tracking a golf swing; however, certain bodily positions, such as the hip, leading knee, and leading foot, did not yield meaningful data as compared to the other positions. The IMU data from the back and front of the wrist and the leading shoulder provided useful mappings of the golf swing, including the timing and intensity. Analysis of body posture angles, especially wrist flexion, hip, and shoulder rotation angles, offered valuable data that may be useful to both coaches and players. By discerning patterns in successful and unsuccessful swings, coaches could provide informed feedback to golfers, aiding golfers in refining their techniques. These findings demonstrate the potential of IMU sensors in golf instruction, offering a data-driven approach to enhance golfers' performance and consistency on the golf course.

***Index Terms*—data-driven coaching, IMU sensors, golf coaching, golf swing analysis, sports technology, swing consistency**

I. Introduction

Golf, a popular sport globally, involves hitting a ball towards a hole in as few strokes as possible [1]. Golf equipment manufacturers invest significant capital in meticulously designing clubs to achieve the perfect balance and a precise centre of gravity. Each club's loft is carefully calibrated to yield varying distances, higher loft translates to shorter distances, while the weight distribution across the clubface's heel, toe, and hosel is harmonized to centre the gravity precisely.

Thus, as golfing gear and technology advance, the golfer should be able to get the ball up in the air with greater ease; however, probably the most important part of the game of golf, relies on the golfer's ability to replicate a predictable and consistent golf swing. Reaching this goal requires extensive practice and, in most cases, a lot of coaching.

In the 1990s, the average American golfer's handicap was 16.3 for men and 29.7 for women [2]; however, there has been an improvement in golfing handicaps. For example, the United States Golf Association (USGA) as published in 2021, found that the average handicap index for men has reduced to 14.2 and 27.5 for women [3]. That is a drop of 2.1 and 2.2 points, respectively. Nevertheless, a major challenge to golfers is to maintain a consistently good swing which requires observation of the golf swing to monitor it and to understand what bodily movement influence different outcomes. It is for this reason that many golfers spend hours at the driving range and/or utilise the services of professional golf instructors to refine their golf swing to be repeatable and reliable.

Golf coaching can be expensive and typically requires many sessions before a beginner reaches a point where they acquire a "feel" for swinging the club. Thus, it is unsurprising that golf is considered a costly sport. Golf, like any other sport, requires practice, and for golf, it is the swing that needs to be consistently good. Attaining a consistently good swing is challenging and often requires additional training accessories and equipment [4]. Coaches should have a trained eye for observing correct golf swings which comes with years of coaching practice. However, even seasoned golf instructors may miss the small movements that make up the golf swing. Further, the average person's reaction time for observing any movement is between 180 and 200 ms [5]. Thus, even good coaches can miss the subtle details in the motion of a golf swing. If, however, an electronic device could be used to map and plot the golfer's swing, both the golf instructor and the golfer could use this data to improve the swing.

The shoulder joint is crucial for a consistent golf swing. Not only are the shoulder muscles important, but so too are the muscles that support the shoulder blade—trapezius & levator scapulae which contribute to the swing's effectiveness [6]. Golfers stand with their leading side of their bodies facing the position they want to hit the ball. With the advent of wearable devices, it is proposed that by designing a device that can monitor the body's movement during the golf swing, this in turn can map the movements that influence the ball strike. Thus, it

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is proposed that golfers may reduce their handicap by utilising the correct body movement based on the data derived from an inertial measuring unit (IMU). While studies have attempted to use IMU data to track a golf swing [7, 8], there seems to be minimal research into comparing the placement of the IMU sensors on the body to ascertain which bodily position are useful for golf swing analysis. There is also limited research specifically focusing on the leading shoulder of a golf swing. This location is important as it creates an opportunity to investigate the sequence of body movements around the shoulder to identify the relative movements for creating consistency.

II. Literature review

The complexity and speed of the golf swing poses a challenge for golfers to analyse their motion effectively, prompting the development of various training devices to capture golf swing data. To fully record and measure a golf swing, a high-speed video recording set up would be needed. Vision systems, such as Microsoft's Kinect, video cameras, and specialized clothing have all played an important role in golf swing tracking systems, enabling the detection and monitoring of the golfer's motion [9, 10, 11, 12]. Other video and photographic-based training tools include high-speed video, motion capture cameras, and stroboscopic photography [13, 14, 15], often requiring a meticulous setup and analysis of large data files [16, 17, 18]. Thus, video- and photo-based systems are elaborate, costly, impractical, and are generally used in a lab type setting. IMUs, however, are small, lightweight, and easy to wear and carry around on the golf course. IMUs offer high accuracy and provide real-time feedback and are thus an interesting and viable option in golf swing tracking systems.

A. Micro-electro-mechanical Systems (MEMS) and Inertial Measurement Units (IMUs)

The IMU is an electronic device designed for precise motion sensing and control. It is an electronic device that monitors gravitational forces, acceleration, direction, and angular rates, typically equipped with accelerometers, gyroscopes, and magnetometers [19]. It employs linear accelerometers and rate gyros to measure roll, pitch, and yaw [20]. IMUs are a specific application of MEMS technology [21], characterized by microdevices integrating electrical and mechanical components which have revolutionized various industries due to their small size, low power consumption, and cost-effective fabrication methods [20]. The coordinate system of an IMU sensor establishes a framework for measuring gravitational forces, acceleration, direction, and angular rates[1], as shown in Fig. 1. The 6-axis IMU integrates an accelerometer and a gyroscope, with each axis typically capable of movement of four to six degrees of freedom [22]. The accelerometer, one of the key sensors in an IMU, is responsible for measuring the acceleration of an object along the x, y, and z axes [23].

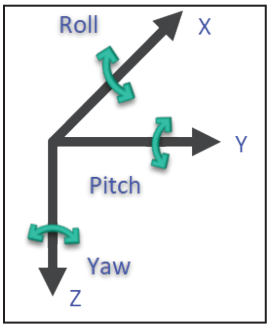


Fig. 1. Coordinate system for a typical IMU.

B. Types of IMU Sensors

The three basic technologies used in IMUs are micro-electro-mechanical systems (MEMS), fibre optic gyroscopes (FOG), and ring laser gyroscopes (RLG). MEMS IMUs have become popular due to their compact size, low cost, and reasonable accuracy. FOG and RLG IMUs offer high accuracy, stability, and precision, albeit at a higher cost. With these capabilities, IMUs are becoming increasingly important in robotics, aerospace, and virtual reality, autonomous vehicles, enabling precise tracking and control of movement in three-dimensional space where precise and reliable motion sensing is necessary. However, the selection of an appropriate IMU technology depends on the specific requirements and constraints for each application [24].

C. Some Applications of IMUs in Sport

Human movement can be measured using sensors to offer a quantitative estimate of physical activity [23, 25]. IMUs are often used for the measurement of physical exercise and activity levels; they can also provide remote coaching, and even offer rehabilitation programmes [23].

Many applications and developments of IMUs have expanded in the fields of sport, including injury prevention and medical rehabilitation [22, 23, 26]. There are numerous considerations that must be studied prior to the use of IMUs. A requirement for IMU use, is to place the IMU as close to the body as possible. This achieves higher accuracy in the sensing data. Thus, the IMU can be part of a band, or incorporated into clothing—the goal is to reduce any motion between the human body and the sensor. The correct placement of the sensor is required to attain relevant and readable data, which greatly relies on where the sensor is positioned. Incorrect placement would result in useless or weak data. For example, breathing patterns during sleep apnoea diagnosis can be detected when the accelerometer is placed on the chest area of the human body, but if the IMU is positioned incorrectly, the data is compromised. Of course, for breathing, the placement is apparent, but for a golf swing, the dynamic motion of most of the body during a golf swing poses a significant challenge to the researcher as to where to place the IMU(s). It is this predicament which necessitates a study on IMU placement for golf swings and thus the one research question for this study addresses the possible location(s) for where IMU sensors are be placed on the body for useful swing data.

[1] An angular rate, as determined by the gyroscopes of an IMU, refers to the immediate rate at which an object is rotating around a particular axis, usually X, Y, or Z. Angular velocity is a measure of the speed and direction of rotation of an object at a specific instant.

D. Errors in IMU Data

One drawback of using IMUs is that they are susceptible to inaccuracies that accumulate over time. This is called "drift." Drift occurs as the device continuously measures differences within itself. When measuring movement over a long period, errors in the data would start to accumulate [27, 28]. The least squared method is commonly used to eliminate this type of error from the data; however, this method tends to produce imprecise results [28]. One way to offset this error is to combine the sensors in complementary pairs [29]. Combining IMUs in complementary pairs involves strategically positioning multiple sensors to capture motion from different perspectives, mitigating drift-related inaccuracies and improving measurement precision over time.

E. Golf Swing Analysis Techniques and Technologies

1) IMU placement – club and/or body

When measuring golf swings, the researcher could choose to track the golf club itself, or the person, or both. This distinction speaks to where the IMUs or tracking device would be placed. An example of golf club tracking was a study whereby the golf swing tracking relied on stereo cameras that track infrared light emitting diodes which are placed on the golf club. This test setup also used an IMU on the golf club [30]. The system calculates a golf club's 3D position and orientation while the golf club is swung. This system thus uses both video and IMUs to track the golf swing; however, the focus is on the golf club's trajectory rather than the golfer's body motion.

In another study, a single IMU was placed on the grip section of the golf club. This IMU was successful in detecting the golf swing movement [31]. This study showed that an IMU can be used for golf swing analysis with respect to the club.

A study whereby the IMU was placed on the golfer's waist area was used to aid a golfer in improving their swing [7]. The IMU was placed in a belt and measured the golfer's angular velocity at a player's waist which the researchers then mapped and compared to what they believed to be a good golf swing. Their system would alarm when the golfer deviated from what they determined to be a good golf swing.

IMUs have also been placed on the golfer's back with the aim of detecting the upper and lower back movements during the golf swing to measure muscle movement of the spinal axis [32]. In this study, which comprised five participants, the researchers observed significant deviations in upper back muscles during swings, which could lead to injuries if not addressed. This method of capturing and analysing data can be applied beyond golf, offering insights into patterns of muscle movements and injury prediction [31]. Thus, the placement of the IMUs can be used for both the tracking of the club as well as for the tracking of the human body, each providing useful data for the golfer and/or trainer.

F. Shoulder Kinematics and Injury Prevention

Golf, while not considered a high impact sport, still sees professional athletes (and novices) experience injuries. Golf-related injuries occur when poor swing mechanics are utilised, with between 8% to 21% being shoulder injuries [33, 34]. To better understand shoulder movements during the golf swing, researchers often utilize methods such as motion tracking to capture and analyse the intricacies of shoulder movement. Additionally, electromyography techniques are employed to monitor muscle activity in the surrounding muscles of the shoulder joint. In studies focusing on expert golf performance, researchers have observed that different muscles become active during various phases of the swing, indicating sequential muscle activation [35, 36].

A study of 108 golfers analysed shoulder kinematics and found that shoulder movements vary between age groups [33]. The study also indicated that shoulder movements declined with age. Other anomalies included the senior age group tended to lift their right arm higher at the end of the backswing. This data could help professional coaches provide targeted coaching advice for different age groups. The study thus highlights the importance of understanding shoulder kinematics of golf swings [33]. Understanding the range of motion that amateur golfers achieve can greatly improve effective training methods [35, 37]. This understanding allows coaches to tailor their approaches to better suit the physical capabilities and limitations of amateur golfers, leading to more targeted and efficient training programs. For example, in another study, four wearable sensors were placed on the body to capture sensor data from two groups: experienced and novice golfers [8]. The sensors provided accelerometer and gyroscope data, revealing distinct differences between beginners and experienced players when performing a golf swing. The researchers then used this data to enhance the performance of beginners by providing textual feedback displayed on a mobile device. Thus, by tracking the body's dynamic movements, golfers stand to benefit and possibly reduce their chance of injury.

G. The Stages of a Golf Swing

To analyse a golf swing, it is important to delineate the body movements during the golf swing as depicted in Fig. 2. These body movements are as follows: address (1), backswing (2 & 3), downswing (4), impact (5), and follow-through (6) [38].

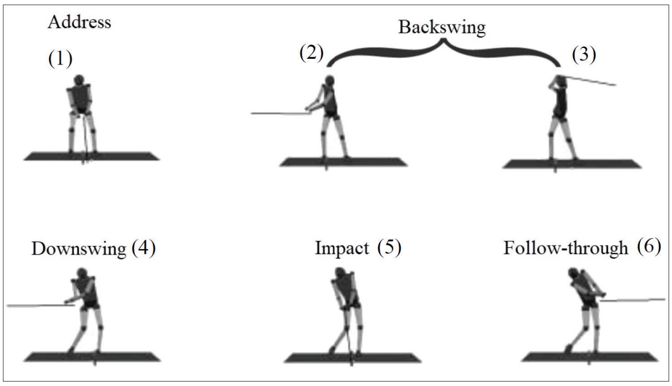


Fig. 2. Six golf swing stages adapted from [33].

These six movements are described as follows:

Address: The initial position before the swing involves alignment with the target, gripping of the club, and positioning of the body. The golfer places the clubhead behind the golf ball. During the transition from the address to the backswing, the wrists, arms, and shoulders twist upward, and the hips spin around the body's vertical axis.

Backswing: The motion of taking the club away from the ball, characterized by body rotation, arm extension, and club elevation. The grip end of the club reaches the highest position with the greatest rotation angle at the peak of the swing.

Downswing: The movement bringing the club down towards the ball is characterized by rapid body rotation, arm and hand motion in a downward direction, and weight transfer from the back foot to the front foot. During this phase, the twisted or rotated angles of the hips, shoulders, arms, and wrists are released, and the club is swung downwards from the top to the downswing.

Impact: The critical moment of contact between the clubface and the ball considering that the ball deforms at this point and thus the impact between clubface and ball occurs for some time until the ball leaves the clubface.

Follow-through: The continuation of the swing after impact involving the club's movement towards the target with full body rotation and the extension of arms [39]. Following impact, the motion shifts to follow-through before reaching the finished position [40].

III. Pilot Study on Measuring Golf Swings with IMUs

This study aims to establish the efficacy of IMUs in capturing movement patterns during different phases of the golf swing and to explore their potential for improving swing consistency among players. To achieve this, the study comprised of several stages. An overview of the process is as follows: The first stage (selecting viable IMUs) involved systematically identifying a range of IMUs. After the shortlisting of IMUs, practical simulated tests were undertaken to ascertain whether such IMUs would be suitable for golf swing analysis. Once the practical simulated tests were undertaken, a participant study was completed for real-world golf swing trials with the aim of determining the minimum number and optimal positioning of IMUs needed for golf swing mapping.

A. Selecting the IMUs

Choosing the right IMUs was a critical part of this study. To reach the study's objectives, a set of criteria was created as listed in Table 1. Criteria including the sampling rate, current usage, cost, and so forth, were used to compare the shortlisted IMUs. These criteria were compiled based on the needs for this study. These IMU specifications were then compared.

TABLE I
The Selection Criteria Used to Shortlist the IMUs for This Study

Selection Criteria	**Models:**	ISM330DHCXTR	BMI270	BMX160	LSM6DSLTR	MPU-9250	BNO055	ICM-20689	MPU-6050
Market Availability (RSA)	In stock		●						
	Zero stock	●		●	●	●	●	●	●
Product Status	Active	●	●		●		●		
	Discontinued								
	Last time buy			●					
	NRND							●	●
	Obsolete					●			
Output type	SPI	●	●	●	●	●		●	
	I2C	●	●	●	●	●	●	●	●
	UART						●		
Cost (ZAR)		190.74	144.15	459.13	107.14	286.89	304.11	129.51	153.23
Dimensions (mm)		2.5x3.0	2.5x3.0	2.5x3.0	2.5x3.0	3.0x3.0	3.8x5.2	4.0x4.0	4.0x4.0
Height (mm)		0.86	0.83	0.95	0.83	1.0	1.13	0.9	0.9
Accelerometer range	up to 16g	●	●	●	●	●	●	●	●
Gyroscope range	up to 2000°/s	●	●	●	●	●	●	●	●
Max. sampling rate (Accelerometer)		6.6KHz	1.6KHz	1.6KHz	6.6KHz	4KHz	1KHz	4KHz	1KHz
Max. sampling rate (Gyroscope)		6.6KHz	6.4KHz	3.2KHz	6.6KHz	8KHz	1KHz	8KHz	8KHz
Auxiliary inputs		●	●	●		●			
Evaluation PCB option		●	●	●	●	●	●	●	●
Additional sensors	Temperature	●			●			●	
	Magnetometer			●		●	●		
Current (mA)	High-performance mode	1.2	0.97	1.585	0.65	N/A	N/A	3.2	N/A
	Normal mode	0.7	0.685	N/A	0.45	3.7	12.3	1.27	3.9

After completing a comparative analysis, three IMUs were selected as the best options for this study. To follow are the three IMUs that were chosen and the reasons thereof:

IMU 1: LSM6DSLTR from STMicroelectronics was chosen for its cost-effectiveness, availability, and support for both inter-integrated circuit (I2C) and serial peripheral interface communication protocols, making it suitable for wearable applications.

IMU 2: ICM-20689 from TDK InvenSense was included for its high sampling rates despite being slightly more expensive and not recommended for new designs.

IMU 3: MPU-9250, also from TDK InvenSense, stood out due to its onboard magnetometer, low-power mode, and integrated motion processing algorithms, justifying its inclusion despite being the most expensive option.

It was concluded that these three IMUs collectively provided a range of features necessary for the purpose of this study. A further requirement was that the selected IMUs must all have an evaluation board to reduce the need to design and print a separate PCB.

B. Practical Simulation of a Golf Swing Using a Test Rig

A practical simulation of a golf swing was needed to verify that the chosen IMUs would indeed track a golf swing. To simulate a golf swing in this study, polyvinyl chloride (PVC) pipes were used to build a test rig as shown in Fig. 3. PVC was chosen because it stays rigid during the swinging motion and stays the same distance from the ball at the point of impact. PVC is known for being light and having only mild elastic properties. During the downswing phase, however, a small lateral sway in the vertical PVC pipe was observed (point A in the figure). This was because the club's motion towards the ball created momentum. The IMUs are shown at point B in the figure.

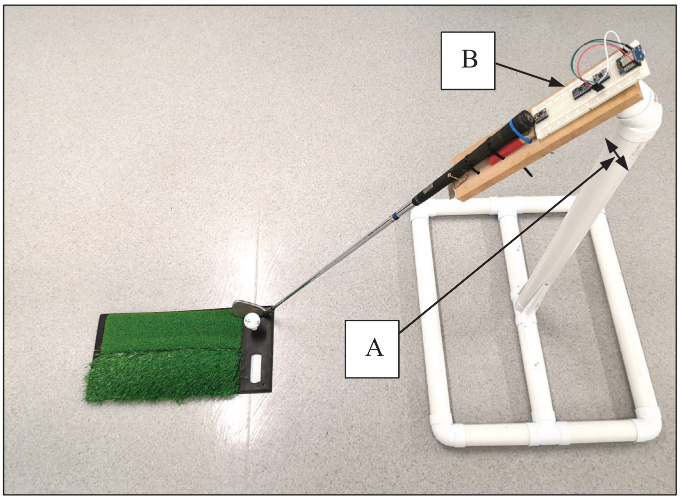


Fig. 3. Side view of the test rig used to evaluate the shortlisted IMUs.

The PVC test rig shown in Fig. 3 was used with all three IMUs to determine if each IMU was able to provide useful swing data. Several "swings" were undertaken, and the data was analysed. An example of the IMU data is shown in Fig. 4.

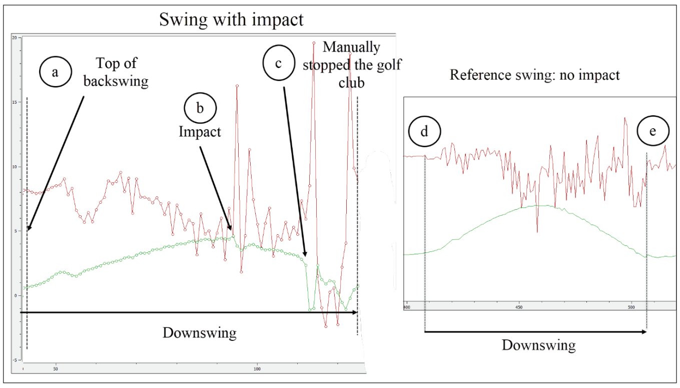


Fig. 4. The resultant waveforms of the simulated golf swing for the LSM6DSLTR IMU when used on the purpose-built test rig.

Fig. 4 shows the result of the mapped simulated downswing that was produced using the test rig. The figure contains two windows: the one on the left depicts the simulated downswing with impact (club hitting golf ball), while the window on the right shows the swing with no impact (reference). The simulated swing revealed that the angular velocity (green plot) increased after the club was released which was as expected. The noisy red plot shows an almost constant acceleration (if the entire plot is averaged); however, the red plot does show high peaks which were the result of the flexing of the test rig.

Points (a) to (c) in Fig. 4 depict the recording from the top of the backswing, with the point of impact at (b). The point of impact on the graph is where there is a sudden change in the direction of the red plot. There is also a moderate change in the angular velocity's plot at the point of impact. The clubface impacts the ball during the downswing (b), followed by a downward trajectory in the green plot after the impact point, as depicted in Fig. 4. The point of impact is typically at the lowest point on the downswing. According to Newton's third law of motion, when an object—golf ball—makes contact with another object—golf club, it applies a force to the club, which is met by an equal but opposite force. Since the green line on the graph represents angular velocity measured in degrees per second, it shows a change in direction at the moment of impact (b). Thus Fig. 4's green plot can be used to represent the swing phases (from backswing to follow through).

The plot from (d) to (e) shows the start of a backswing until where it was manually stopped when there was no impact.

The simulation only focused on the downswing phase of the golf swing, as the club was stopped after making contact with the ball. After performing the practical simulations on the test rig, it was noted that the accelerometer's data was noisy (red plot) and would need filtering.

This PVC test rig (Fig. 3) was not meant to be an exact replica of a human golf swing, but it did its job of collecting IMU data during certain parts of a simulated golf swing to confirm that the three selected IMUs would be capable of tracking a human's golf swing. The three IMUs were also able to track the slight lateral sway exhibited by the PVC prototype, which is similar to a human swinging—further supported the conclusion that the IMUs were a good choice for the participant study as it is assumed the IMUs would also capture a human's sway.

C. Human Trials

Following the simulated golf swing tests using the PVC rig, the three selected IMUs were used in a participant study. This study was conducted with six participants who were conveniently sampled. The participants comprised of four males and two females. The shortest person was 1.59m tall while the tallest was 1.89m. The participants' ages ranged from 27-38 years old. The body mass index of the participants ranged from 25 to 36. The group consisted of golfers who were at beginner level as well as experienced golfers. Ethical clearance was provided by the University of Johannesburg and all participants were informed of how the voluntary study would take place. For this pilot study, eight possible locations on the human body were identified for IMU placement. These positions represented locations on the leading edge of the body from the ankle to the shoulder as depicted in Fig. 5. The leading side of the body was used as there are not many publications (if any) on the tracking of the leading side of the body with an IMU.

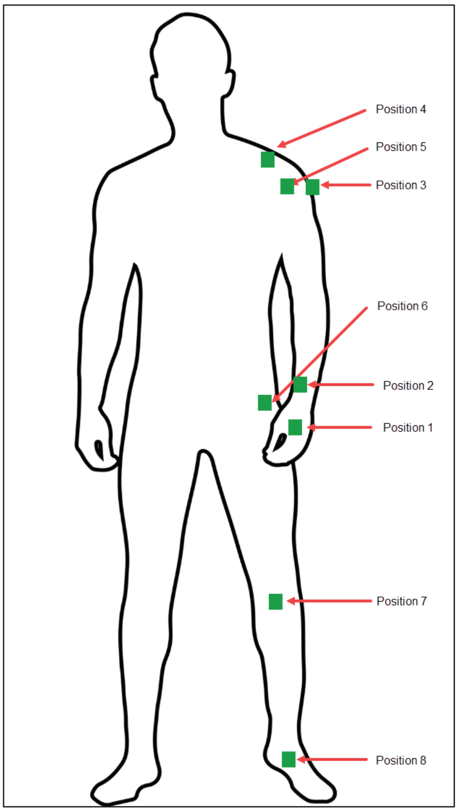
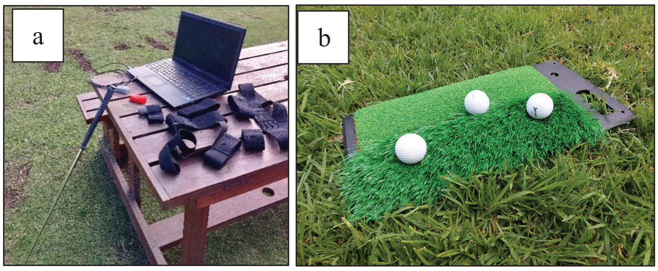


Fig. 5. The eight sensor placement positions used in this study.

Each participant was asked to perform a total of 72 golf swings. Participants performed golf swings while sequentially moving the IMUs to eight positions, generating substantial data. The IMUs were securely placed close to the body using purpose made elastic fabric bands (Fig. 6a). After each set of three swings took place for each position, data extraction and IMU repositioning commenced as the next position was tested. A participant thus needed to complete a total of 72 swings—three swings per position x three attempts x three IMUs. For each position (positions 1-8 as shown in Fig. 5), three trails were undertaken to account for any anomalies.

It must be noted that for each bodily position, three IMUs were used sequentially. This means that after the three swings occurred with IMU 1, that IMU was swapped with IMU2, to which the participant performed another three swings, and then once again for IMU3. This process was then repeated eight times to cater for the eight pre-selected positions on the body which totals 72 swings. Since there were six participants, a total of 432 golf swings were analysed (although more than this took place). While one may assume that all three IMUs should have been tested simultaneously, the goal was to position each IMU as close to the body as possible. Due to space limitations, it was not feasible to achieve this without testing each IMU (and associated development board) sequentially.

To respect bodily privacy, participants were shown how to move the IMUs themselves; however, researcher assistance was available upon request. The average test duration was 1.5 hours per participant. Participants were provided with a seat and their comfort was regularly assessed. Figs. 6 a & b shows some of the equipment used, including elastic fabric bands, the laptop for data extraction, and the golf club for the swings.



Figs. 6a & b. Test setup and equipment for practical tests including the purpose made straps and the artificial grass mat.

As part of this pilot study, the researcher consulted with participants to gather advice on the use of an artificial grass mat instead of natural grass. Since one participant favoured an artificial grass mat, citing a consistent ball placement and ease of swing initiation, a grass mat was available for those who preferred this option. Point A in Fig. 7 shows one participant standing on the grass, where the ball must move further back on the grass after each swing because of the divot created after impact was made with the ball. This situation highlighted the challenges of natural grass, requiring frequent adjustments compared to the artificial grass mat that provided a more stable and comfortable starting point for the swing.

Fig. 7. Golfer orientating his feet and ball level by doing practice swings (hitting the ground).

D. IMU Placement and Data Collection

Fig. 5 shows the specific bodily positions where IMUs were placed for recording of the golf swings. Since there are only a few studies on IMU placement that focus on only a small number of bodily positions [33, 41], this pilot study experiment utilised multiple positions. The aim was to answer the question of which position(s) are best for golf swing analysis.

The IMUs were positioned at eight distinct bodily positions as shown in Fig. 5:

- Position 1: Back of the leading hand.
- Position 2: Back of the leading wrist.
- Position 3: Side of the leading shoulder.
- Position 4: Top of the leading shoulder.
- Position 5: Front of the leading shoulder.
- Position 6: Leading side of hip.
- Position 7: Front side of leading knee.
- Position 8: Leading foot.

The testing involved three different IMUs, each recording the swings. Data was stored in CSV files on the device and then transferred to a laptop. A Python script, which was purposively created for this study using PyCharm IDE, was used to extract the data. This script was also coded to automatically create graphs of the data, facilitating swing logging.

The CSV files provided datasets including timestamps, acceleration (accel-X, accel-Y, accel-Z), baseline values (baseline-X, baseline-Y, baseline-Z), and gyroscope readings (gyro-X, gyro-Y, gyro-Z). The term “baseline” refers to the initial or default readings of the accelerometer and gyroscope sensors when there is no motion. These baseline values are crucial for accurately analysing changes in acceleration and angular velocity throughout the recorded movement.

E. Data Analysis

Each IMU is equipped with a triaxial accelerometer and a triaxial gyroscope which record acceleration and rotational changes in three dimensions. One may calculate the total acceleration by squaring the acceleration values along each axis, adding them, and calculating the square root of the sum. This value measures the acceleration intensity independent of direction [7, 42, 43]. Thus, in this study, the magnitude of the accelerometer and gyroscope was first calculated by using the formula below:

$$Magnitude = \sqrt{(x^2 + y^2 + z^2)} \qquad (1)$$

The above formula used for the accelerometer assists in determining the overall acceleration experienced by the IMU sensor. Similarly, the magnitude for the gyroscope uses the same formula as the accelerometer albeit now for angular velocity. Thus, the size of the rotational movement can be calculated by squaring the angular velocity values along each axis, adding them together, and calculating the square root of the sum. This magnitude shows the rotation's full strength, regardless of its direction. The magnitudes of the accelerometer and gyroscope are calculated to assist in understanding the total amount of acceleration and angular velocity recorded by the IMU sensor. These magnitudes thus provide helpful indications of the strength of the motion and resultant forces measured at the bodily position tracked by the IMU.

After performing the practical simulations on the test rig, it was noted that the accelerometer’s data was noisy (as shown in Fig. 4), and from the literature scholars have also noted that the data from the gyroscope does become inaccurate over time due to drift that occurs within the IMU sensor [27, 28]. Owing to this challenge, after many trials with different filter profiles, a 10th order Butterworth low-pass filter, with a cutoff frequency of 10 Hz, was applied to the recorded IMU data. This choice of filter was also found to be useful in [44, 45].

Filtering is also important for visually plotting the data, making it smoother and easier to visually evaluate because it reduces high-frequency noise that can make it difficult to observe the underlying swing patterns; however, the dampening of the filter is important. If its overly damped, then the response times and sensitivity reduce. Under dampening permits too much noise through, thus, a compromise is needed which necessitates extensive filter parameter trails.

F. Summary of the procedure for the processing of IMU data

To follow is a summary of how the processing of the IMU data took place as well as a short description of the graphing template used for the displaying of the results in the upcoming sections.

1) Importing and preprocessing of the data was as follows:
   a) Three golf swings were recorded and stored into one CSV file.
   b) The researcher runs a Python script that imports data from a CSV file and divides the swings into separate CSV files for each detected golf swing.
   c) Each CSV file has columns with timestamps, accelerometer data (X, Y, and Z components as depicted in Fig. 1), baseline data (X, Y, and Z components), and gyroscope data (X, Y, and Z components).
   d) The time axis for the plots is set by the timestamps which originate from the participant performing a swing.
   e) The magnitude is then calculated for the accelerometer and gyroscope as in formula (1).
2) Filtering to reduce noise:
   a) A 10th order low-pass Butterworth filter is applied to reduce noise in the accelerometer and gyroscope data.
3) Displaying the data. With respect to the upcoming Figs 8-20, the following convention was set:
   Accelerometer data (Red graphs shown in Figs. 8-20):
   a) A subplot is generated for accelerometer data by a graph plotting script which is plotted in red.
   b) The x-axis shows time, and the y-axis shows acceleration.
   c) The accelerometer magnitude for one IMU is shown in each subplot.
4) Showing the data from the gyroscope (Blue graphs with respect to Figs 8-20):
   a) A subplot is generated for the gyroscope data that is similar to the subplot for accelerometer data.
   b) Time is shown on the x-axis, and angular velocity is shown on the y-axis.

G. Displaying the phases of a golf swing from IMU data

Fig. 8 is an illustration of how this study identifies the different phases of a golf swing. The phases of the swing are demarcated by letters (a) to (d); however, one needs to keep in mind that this demarcation is based on a qualitative interpretation from the hundreds of graphs that were analysed from this study as well as from the findings from other studies [33, 38]. Thus, the phases are not exact demarcations but highly probable considering the gyroscope and accelerometer data.

From Fig. 8, the address would be before point (a). As soon as the golfer lifts their club, they have started the backswing. This is depicted by (a) and continues until (b). In the backswing phase, the golfer lifts the club and the club speed increases from rest to reach a maximum speed just after mid-way in the backswing travel. The club speed starts reducing as the club approaches the top of the backswing. In the blue gyroscope plot, the trace shows an increase in angular velocity from (a) and increases steadily to (i) thereafter reduces to a minimum at (ii). This minimum angular velocity at (ii) would signify the beginning of the downswing (b) which is also a direction change in the motion of the golf club and arm movement.

It is expected that the downswing will have a much faster tempo than the upswing. This is shown by the steeper gradient which starts just after (ii).

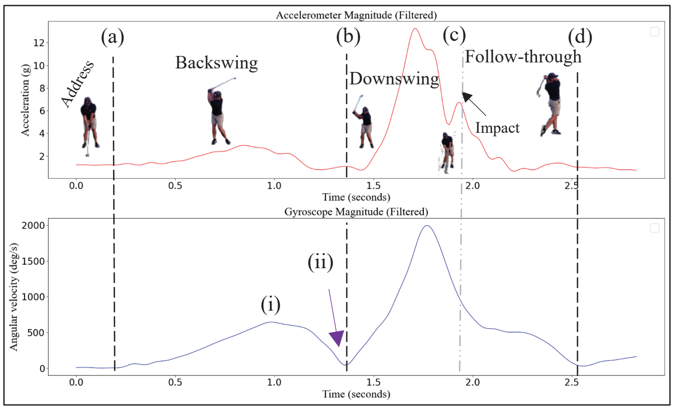


Fig. 8. Identifying the swing phases of a golf swing using two subplots of acceleration and angular velocity from IMU data.

The plot between points (b) and (c) is considered the downswing phase. Point (c) is the approximate point of impact[2] with the ball (noting that the club and ball remain in contact for a certain period). Point (c) shows a change in acceleration as the trace went downwards and briefly went in the opposite direction (red graph of Fig. 8). The trace between the points (b) and (c) is faster than the backswing phase which is as expected as the downswing of a golf swing is faster than the backswing. This indicates that this is the range in the downswing where higher speed is generated to increase the swing force of the club.

The end of the downswing is considered the point after the impact is made. It is noted that the club does deflect in the opposite direction to the motion of the club. After the impact zone marked at point (c), the change in the measured data takes a bit longer to reach a point of no movement—indicating the follow-though phase where a golfer would reach the finish point for their swing. After the impact phase, the swing is slowed down because accelerating further will not make a difference in determining the ball speed and direction. Using the typical demarcations (a) to (d) as shown in Fig. 8, the results for the eight positions are now presented.

IV. ANALYSIS OF RESULTS

The results from the eight IMU bodily positions are shown with their associated graphical representations in Figs. 9-16. At least 54 dual waveforms were computed for each position (1-8 as demarcated in Fig. 5) and thus there was extensive data for this part of the study (over 864 individual graphs). Since there were six participants, each with their own unique golf swing, there was some variety in the waveforms for each position; however, there was conformity in the general shape and trend for the graphical plots for each bodily position and thus only a single typical example of the data captured for each position is shown. The analysis starts with position 1 where the IMU was placed on the back of the participant's hand.

1) Position 1: IMU placed on the back of the leading hand (Fig. 9)

The phases of the golf swing based on this position's data was determined as follows: The start of the swing is indicated by the dotted line (a) and the end of the swing is marked as (d). As already described earlier, at the start of the golf swing, the club and arms would accelerate in an upwardly direction which would start at (a) and continue until (b). During this backswing phase, and since the IMU was placed on the hand, there was a noticeable reduction in the participant's hand speed (at the club handle) shown at zone (i) in the gyroscope plot (bottom graph in blue) of Fig. 9. This suggests that the golfer is moving into the downswing phase. This can be distinguished from the earlier part of the plot depicted by the green arrow (ii).

At (i), there is a clear shift in direction that was detected—indicating a brief stop in the participant's backswing. This halt is visible in the gyroscope data after the green arrow line section where there is a negative trace of the purple line and is substantially shorter than the first phase of the backswing (green line at (ii)). At the top of the backswing, the club comes to a momentary stop but then the golfer thrusts the club downwards with an increasing acceleration which is then downswing part. This first part of the downswing is depicted at the section between (b) and (c) just prior to impact. The downswing begins at (b) and shows an increasing acceleration until the plot approaches (c)[3].

Zone (iii) suggests that there was a slight decrease in acceleration during this first part of the downswing because the plot showed a slight hump at (iii). This implies that there was a change in the golfer's tempo. This plot that had this "hump" (iii) was specifically presented for this example to show how the IMU can track the golfer's unique golf swing style. This data is useful in advising the golfer about their downswing consistency.

This position whereby the IMU was placed on the back of the hand provided a clear waveform to identify a golf swing when analysed with reference to the demarcations of the phases of the golf swing shown in Fig. 8.

[2] Although this plot does show a noticeable change in the acceleration plot, other IMU positions do not show an obvious change in acceleration and thus demarcating the exact point of impact can be challenging.

[3] When analysing the many plots from the six participants, one could see variations in the downswing plots, but the overall trend aligns with the conception that the acceleration increases rapidly after there was a slight pause as shown in (i).

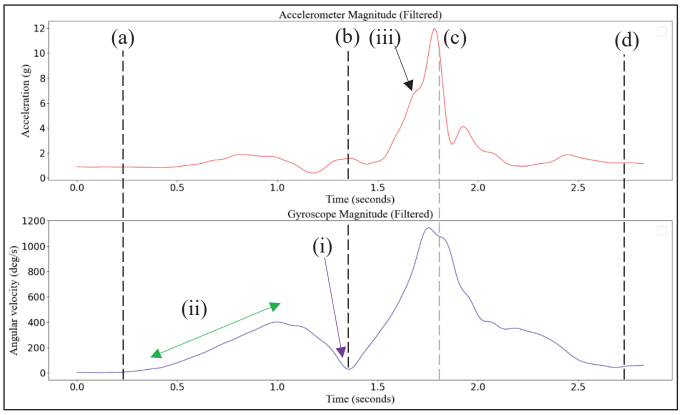


Fig. 9. Example of a swing for IMU placement in position 1 (Back of hand).

2) Position 2: IMU placed on top of the leading wrist (Fig. 10)

The flat area before point (a) in Fig. 10 on both the blue and red graphs was where the participant addressed the golf ball; hence, no noticeable movement shown. The trace thus started moving in an upward direction after point (a), which marks the start of the backswing. The gyroscope's graph at point (i) indicates the highest acceleration for the backswing. The positive tracing is almost the same length as the negative trace between (a) and (b) which looks a little bit like an inverse parabola. The negative tracing after point (i) indicates that the golfer started to decelerate the club to stop it at the top of the backswing which is marked at point (b).

As the downswing phase started after point (b), the rate at which both graphs trace upwards, show the wrist speed is significantly faster than during the backswing phase. Point (ii) depicts the point at which the wrist makes a movement during the downswing phase, right before the impact zone (c). After the impact zone at point (c), the follow-through phase started and had an uneven movement pattern. The end of the follow-through is marked at point (d).

This location is worth monitoring, as skilled golfers tend to release their wrist joints much later than novice golfers [46]. Overall, this position was also usable for demarcating the phases of a golf swing and can also provide useful data about how the golfer's wrist moved during the golf swing.

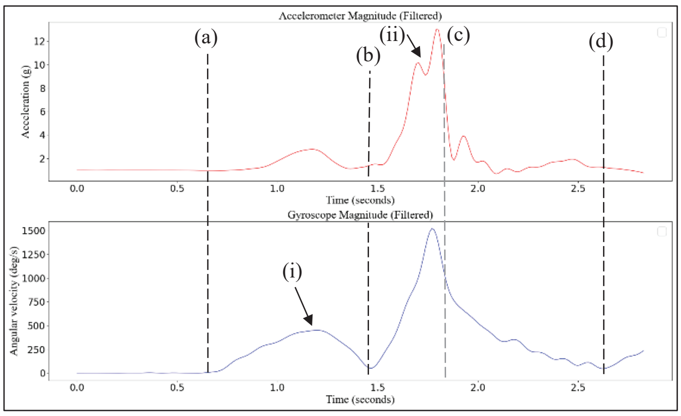


Fig. 10. Example of a swing for IMU placement in position 2 (Leading wrist).

3) Position 3: Side of leading shoulder (Fig. 11)

During the downswing phase between (a) and (b) in Fig. 11, zone (i) indicates a flat section on the graph where the acceleration did not show any increase or decrease. This flat region signifies a constant movement, suggesting that during that specific timeframe, the leading side of the shoulder remained stable. It was expected to see fluctuations in acceleration as some golfers tend to pivot around the centre of their body. This means the lifting or dropping of the leading shoulder of a golfer can impact their swing technique, influencing their posture and the lowest point during the downswing, resulting in either hitting too far in front of the ball or on top of the ball.

The point before the impact point (c), just exceeded 5 g during the downswing, indicating a slower acceleration compared to position 1 or position 2 (≈12 g) which was as expected since position 1 and 2 are closer to the club. Position 3 shows the importance of monitoring the leading side of the shoulder as research also shows that the shoulder's movement differs according to different age groups [33]. It is noted that at point (c) there is almost a momentary pause in the deceleration which signifies the participant's shoulder movement was not uniform—possibly making a sudden correction while swinging. Overall, this position was also useful in demarcating the phases of a golf swing.

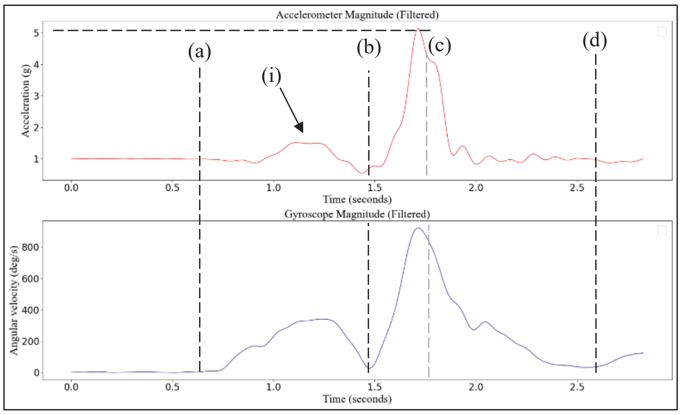


Fig. 11. Example of a swing for IMU placement in position 3 (Leading shoulder).

4) Position 4: Top of leading shoulder (Fig. 12)

Position 4 is quite similar to position 3 as they both are measuring the leading shoulder, although the IMU is placed slightly differently. The top of the shoulder position was thus also able to show the phases of the golf swing. The acceleration graph indicates that between points (i) and (ii) during the downswing phase and shortly after, the participant seemed to follow a more consistent motion and did not make a sudden correction in their swing, indicating better contact with the ball. The presence of a slight change before and after the peak in the gyroscope's graph (iii) and (iv), indicates that there was minor movement of the shoulder throughout the downswing though, notably near the ball's impact region.

The angular velocity was expected to plot a smooth graph similar to the acceleration graph, but the small adjustments during the downswing caused the change in direction. This position still seems useful for the monitoring of the phases of a golf swing as found by [33]. This position also holds potential for the analysis of the golfer's movement of the leading shoulder.

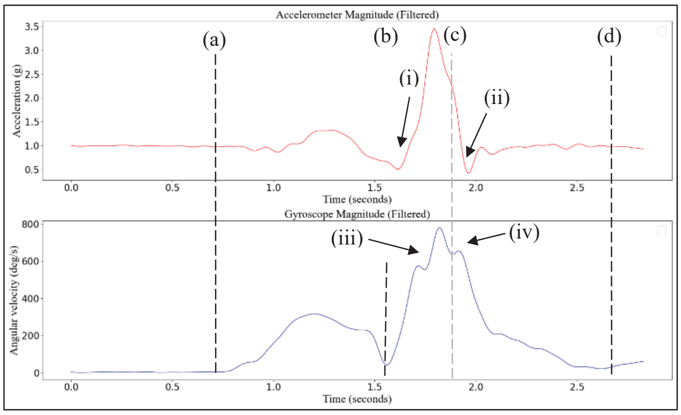


Fig. 12. Example of a swing for IMU placement in position 4 (Top of shoulder).

5) *Position 5: Front of the leading shoulder (Fig. 13)*

Between (a) and (b), the movement on the gyroscope's graph indicates a good tempo during the backswing; however, there were some minor fluctuations during this phase as shown by the slight ripple in the accelerometer plot. The gyroscope plot is still clear in showing the backswing though. During the downswing phase which follows point (b), it can be seen that there was a decrease in acceleration during this phase at (i). This slight change in direction marked at point (i), suggesting that this participant made a bodily correction during the downswing. The front of the shoulder is often used during the golf swing for stabilization. At (ii), it seems that the shoulder was also stationery for a short time. Overall, this position was also usable for demarcating the phases of a golf swing when considering the gyroscope graph.

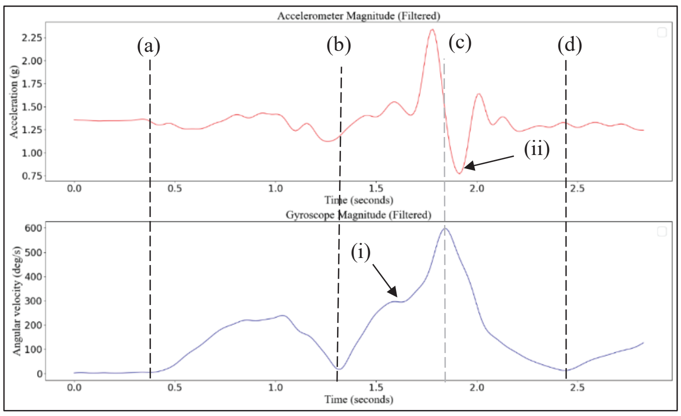


Fig. 13. Example of a swing for IMU placement in position 5 (Front of shoulder).

6) *Position 6: Left side of the leading hip (Fig. 14)*

There was a bit of movement in the leading hip during the backswing, although it was quite slow as shown at (i). However, only during the downswing did the participant start to accelerate with their hips. It is worth noting that by mapping these speeds, golfers and their trainers can get benchmarks as to the "normal" ranges of hip motion. The same is true for the shoulder and other body parts, which, once benchmarked, provide useful diagnostic value in comparing golf swings.

One can also compare different positions and/or golfer's IMU data with each other. For example, the small image within Fig. 14 illustrates the shape that was expected for the hip acceleration during the swing phases for this position. There is a part in this small window marked with point (ii) which shows the expected trend, but this result was not found in the acceleration graphs when the IMU was placed on the hip.

It was anticipated that there would be a pronounced acceleration waveform during the downswing phase, as many golfers tend to open their hips during the downswing. Conversely, when hip movement is less active during the downswing, it often indicates reliance solely on the arms for striking the ball. This reliance typically necessitates bodily corrections to ensure proper contact with the ball. By analysing the phases of the swing and the resultant ball placement, golfers may be able to achieve increased consistency in their swing. Overall, this position was still useful in analysing the phases of the golf swing although this would be interpreted mostly from the gyroscope graph.

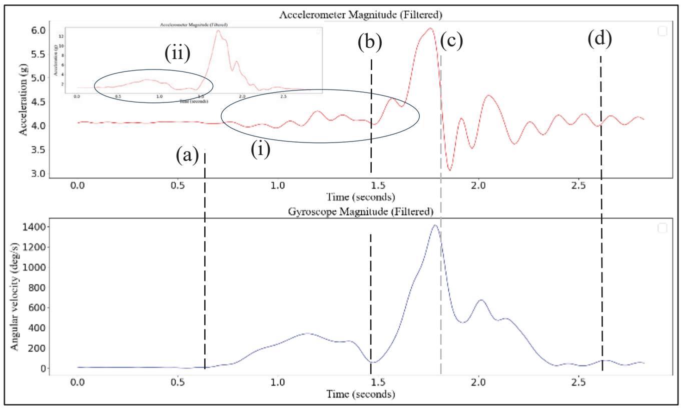


Fig. 14. Example of a swing for IMU placement in position 6 (Side of hip).

7) *Position 7: Leading knee (Fig. 15)*

Fig. 15 shows an example of the response when the IMU is positioned on the leading knee. It is a bit unclear where each swing phase occurred. After careful analysis, it was determined that the downswing would be between (a) and (b). The impact would be around (c), but this cannot be verified as there is another peak with the same magnitude shortly after the proposed impact point in the angular velocity plot. The accelerometer also had one point in time where the acceleration was higher than the average peaks detected, marked as point (i) which increased the complexity in discerning the phase of the golf swing.

There were two places where movements were detected by the gyroscope shown by (ii) and (iii) in the bottom plot. These movements also had a lower angular velocity which was expected as the knee does not move as much as the body parts above it (wrist, shoulder etc).

In terms of demarcating the golf swing phases, this bodily position created a challenge for accurate analysis as golfers can shift their weight during different phases of the golf swing which also impacts the analysis.

It was expected to see controlled movement during all phases of the golf swing for the knee; however, this was not the case for this pilot study from these six participants. The waveforms from this position showed the opposite of what was expected. It was concluded that this position would need a follow up study to assess this position on more participants but tentatively speaking, this position seems to be an unreliable position for golf swing phase analysis as at least 54 graphs were qualitatively analysed, which for the most part, had a similar response in the layout of the plots. This position is however still useful in mapping what the knee is doing during the phases of the golf swing.

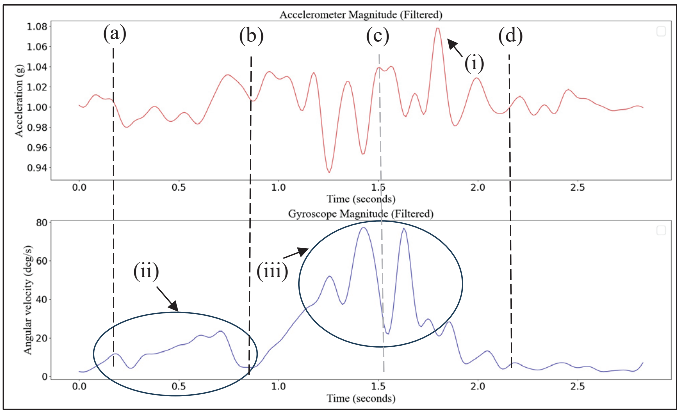


Fig. 15. Example of a swing for IMU placement in position 7 (Leading Knee).

8) Position 8: Leading foot (Fig. 16)

The consecutive peaks for both plots make it difficult to discern unique phases of the golf swing. There is no single significant peak in the figure to use as a reference which makes it challenging to identify golf swing phases. This position, like position 7, was thus found to be unreliable in depicting the phases of the golf swing. There is not much movement in the left foot and thus the plots do not provide much to work with. The reader may be wondering why this position was included in the first place, the answer is that during a golf swing there is a weight transfer between the left and the right side of the body which is also often used as part of golf swing analysis. However, from the IMU data, the results were unintelligible and thus a pressure plate placed under the feet would be a better tool for this analysis.

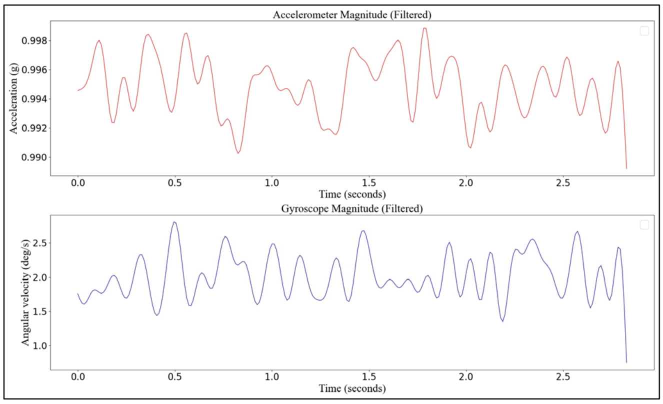


Fig. 16. Example of a swing for IMU placement in position 8 (Leading foot).

V. Discussion

The research questions for this pilot study aimed to determine whether IMU data can map a golf swing from various bodily positions as well as what would be the minimal number and best placement of such IMUs. While studies have shown that the phases of a golf swing can be mapped using an IMU on the club and body [30], what is less clear is how tracking the different bodily positions support golf swing analysis. From this study the best position for depicting the phases of the golf swing was found to be the hand, wrist, and around the shoulder (positions 1, 2, 3, 4, and 5) stated in the order of priority.

The reason for mapping the golf swing is based on the premise that if the phases are clearly demarcated, golfers and/or their coaches can then use the IMU data from various locations on the body to analyse the individual movements of the different body parts to achieve a more consistent golf swing. However, to analyse a specific body part in the dynamic golf swing, one would first need to delineate the phases, and once determined, an analysis of the specific body part and its movement can occur. This point highlights the role of using more than one IMU—one for precise golf swing phase demarcation, and the other for analysis of that particular body part, notwithstanding that both (or more) can be used concurrently for a deeper golf swing analysis.

Once the phases of the swing are known, golfers can then focus on the data for the specific body part. For example, analysing data from the sensor on the back of the hand (Position 1) provides valuable data for golfers seeking to improve power transfer in their swing (as shown by the significant changes in hand speed observed in Fig. 9 before point (c)). By analysing this data, coaches can identify issues like casting[4] or early extension that hinder power transfer, which are both descriptions of hand movements during the golf swing. Additionally, understanding the ideal hand speed variations throughout the swing phases helps golfers optimize their power sequencing, maximizing clubhead speed at impact. Real-time biofeedback systems can thus utilize data from Position 1 to provide golfers with immediate feedback on their hand movements and its impact on power generation. This allows

[4] In golf coaching, "casting" refers to a common swing fault where the golfer prematurely releases the angle between the club shaft and their lead arm during the downswing.

golfers to practice replicating the ideal hand speed patterns, ultimately leading to a more efficient power transfer and a more powerful swing derived from real-time data.

Data from the sensor placed on the top of the wrist (Position 2) highlights a different, but equally important, aspect of swing mechanics: wrist stability (Fig. 10). Unlike Position 1, which focused on power transfer, analysing data from Position 2 assists coaches in identifying excessive wrist movement—a common problem that can impair both power and accuracy. Uncontrolled wrist movement disrupts the optimal sequence of body movements for power generation, reducing potential clubhead speed. It can also cause the clubface to deviate from its intended path at impact, resulting in a low accuracy mishit shot. Using data from Position 2, coaches can recommend targeted drills or swing adjustments to promote better wrist stability. This, in turn, can significantly improve a golfer's swing, allowing them to generate more power and accuracy.

Shoulder injuries are common in golf [33, 34] and thus measuring shoulder movement is imperative in mitigating injuries and thus analysing data from the sensor on the leading side of the shoulder (Position 3) provides valuable insights for golfers. For example, golfers and/or their coaches can use the IMU data to track the shoulder to determine whether there is shoulder stability throughout the swing. Shoulder stability is critical for maintaining good posture and alignment, which are both required for a powerful and controlled swing. Coaches can use this data to identify issues, such as swaying or dipping, which can affect posture. Additionally, real-time biofeedback systems relying on IMUs can use the data from Position 3 to help golfers understand how their swing mechanics affect shoulder stability. This allows golfers to make adjustments while focusing on maintaining consistent acceleration through the shoulder, resulting in better posture and a more efficient swing.

Similarly to Position 3, the sensor on top of the shoulder, which was Position 4, also provided valuable data on the golfer's downswing motion, which is crucial for consistent ball contact (Fig. 12). For example, if one had to analyse the acceleration of the golfer’s shoulder as depicted in Fig. 12, the acceleration was quite smooth and controlled. By analysing Position 4’s data, coaches can spot downswing inconsistencies that could cause mishits. Addressing these issues with targeted drills or swing adjustments can potentially help golfers hit the ball consistently, improving distance, accuracy, and reducing mishits.

The sensor on the front shoulder sensor (Position 5) helps golfers optimise power transfer and swing control by revealing their follow-through action (Fig. 13). Balanced follow-throughs help maintain the club's path through impact, straightening the ball and improving accuracy. Coaches can recommend drills or swing adjustments for a more balanced, stable, and powerful finish by analysing Position 5’s data for follow-through imbalances.

The sensor on the left hip (Position 6) shows the golfer's downswing hip rotation (Fig. 14). Power generation requires proper hip movement. Hips are a power source and their smooth rotation (see Position 6 data) transfers power to the clubhead, maximising swing speed and distance.

While analysing Positions 1-6 provided useful insights into various aspects of the swing, data from Positions 7 (left knee) and 8 (left foot) (Fig. 15 and Fig. 16) showed minimal movement and no significant peaks. This emphasises the importance of sensor placement for accurate swing analysis. Focusing on body segments with more pronounced movement, such as the hand, shoulder, and hip (Positions 1-6), provides coaches with more data to evaluate swing mechanics and make recommendations.

In summary, one recommendation from this pilot study underscores the importance of analysing multiple body positions during golf swings to gain insights into biomechanical aspects such as timing, coordination, stability, and energy transfer. This finding contributes to a deeper understanding of swing mechanics and provide valuable insights for refining techniques, optimizing performance, and guiding future research endeavours in golf biomechanics and sports science. By discerning patterns in successful and unsuccessful swings, coaches can provide targeted feedback, aiding golfers in refining their techniques. The results from the different bodily positions demonstrate the potential of IMU sensors in golf instruction, offering a data-driven approach to enhance golfers' performance and consistency on the golf course.

VI. Limitations

The IMU devices were initially selected based on criteria such as market availability, production time, the presence of an evaluation board, as well as a total budget of less than $50 per IMU. When sourcing IMUs, there was a challenge due to a shortage of parts, resulting in fewer available IMUs than planned which influenced the shortlisting of the IMUs listed for this study. This could limit the generalizability of the study's findings since the pool of IMUs studied was limited.

Some identified IMUs met the study's requirements, while others were rendered unusable due to "end-of-life" notices, further restricting options for experimentation.

Additionally, there is a lack of research on how to take multiple IMU measurements that track an entire side of the body during a golf swing. This limitation underscores the need for future research to establish best practices for IMU measurements in sports biomechanics, such as golf swings.

Furthermore, prolonged sensor use may lead to wear and tear, affecting both mechanical and electronic components, thus impacting measurement accuracy over time [47].

VII. Future Study

Variations in the base sampling rates among IMUs can impact data alignment in the time domain, while external factors like electromagnetic interference may lead to varying sensor readings. Addressing these factors is crucial for accurately interpreting the results. Therefore, future research should prioritize enhancements in calibration processes and exploration of advanced filtering methods for IMUs.

Detecting the phases of a golf swing from IMU data relies on a qualitative analysis of the waveforms which is time consuming. Machine learning provides a possible pathway through the creation of predictive models by automating the classification of various golf swing phases. IMU data can then be analysed using algorithms such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs). These algorithms excel at capturing the flow and timing (temporal dependencies) of the data, allowing for a more nuanced understanding of the swing's dynamic characteristics. A system that automatically recognises swing phases in real-time could significantly improve the efficiency of biomechanical analysis, providing valuable insights to golfers and coaches.

Further to this, the use of multiple IMUs used as complementary pairs or even as IMU groups offers a robust solution to the challenge of drift-related inaccuracies commonly encountered in motion tracking systems. By deploying multiple sensors strategically on the body, researchers and practitioners can obtain a comprehensive understanding of motion dynamics from various perspectives and reduce the challenge of the drift that is present in IMU sensors [27, 28], thus improving the overall accuracy of data collection. Over time, this strategy, not only mitigates the impact of drift but also contributes to refining measurement precision, making it a promising avenue for advancing the capabilities of IMU-based motion tracking technologies [28, 29].

An intriguing prospect is the exploration of adaptive sensor fusion techniques employing machine learning. Sensor fusion involves combining data from various sensors to improve system accuracy, reliability, and performance [48]. Such techniques could dynamically adjust the weighting and integration of data from multiple IMUs based on real-time performance and environmental conditions. Using machine learning algorithms to find the best sensor fusion parameters could lead to the creation of a self-adjusting system that adjusts to the golfer's unique traits and the conditions of the course, making biomechanical measurements during the swing more accurate and reliable. This would have helped in this study as the data recorded did not have the same magnitude in acceleration and angular velocity which was a challenge.

Addressing the limitation regarding the lack of information on conducting IMU measurements on one side of the body during a golf swing is another avenue for future research. Investigating biomechanical differences between the left and right sides of the body and utilising machine learning to identify key features indicative of optimal swing performance could be valuable. Creating a model that can do unilateral biomechanical analysis and asymmetry recognition could help us understand how movements on one side of the body affect the swing. This could lead to personalised training plans that are specific to each golfer's biomechanics.

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