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TITLE:

An Inertial Measurement Unit Based Method to Estimate Hip and Knee Joint Kinematics in Team Sport Athletes on the Field

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KEYWORDS:

inertial measurement units, athletes, soccer, hockey, lower extremity, kinematics, injury prevention, performance enhancement, smart textiles, running

SUMMARY:

Monitoring athletes is essential for improving performance and reducing injury risk in team

sports. Current methods to monitor athletes do not include the lower extremities. Attaching multiple inertial measurement units to the lower extremities could improve monitoring athletes in the field.

ABSTRACT:

Current athlete monitoring practice in team sports is mainly based on positional data measured by global positioning or local positioning systems. The disadvantage of these measurement systems is that they do not register lower extremity kinematics, which could be a useful measure for identifying injury-risk factors. Rapid development in sensor technology may overcome the limitations of the current measurement systems. With inertial measurement units (IMUs) securely fixed to body segments, sensor fusion algorithms and a biomechanical model, joint kinematics could be estimated. The main purpose of this article is to demonstrate a sensor setup for estimating hip and knee joint kinematics of team sport athletes in the field. Five male subjects (age 22.5 ± 2.1 years; body mass 77.0 ± 3.8 kg; height 184.3 ± 5.2 cm; training experience 15.3 ± 4.8 years) performed a maximal 30-meter linear sprint. Hip and knee joint angles and angular velocities were obtained by five IMUs placed on the pelvis, both thighs and both shanks. Hip angles ranged from $195^\circ (\pm 8^\circ)$ extension to $100.5^\circ (\pm 8^\circ)$ flexion and knee angles ranged from $168.6^\circ (\pm 12^\circ)$ minimal flexion and $62.8^\circ (\pm 12^\circ)$ maximal flexion. Furthermore, hip angular velocity ranged between $802.6^\circ \cdot s^{-1} (\pm 192^\circ \cdot s^{-1})$ and $-674.9^\circ \cdot s^{-1} (\pm 130^\circ \cdot s^{-1})$. Knee angular velocity ranged between $1155.9^\circ \cdot s^{-1} (\pm 200^\circ \cdot s^{-1})$ and $-1208.2^\circ \cdot s^{-1} (\pm 264^\circ \cdot s^{-1})$. The sensor setup has not been validated, which is a limitation of the current study. Future research should validate the sensor setup with a gold standard (e.g., a valid optoelectronic motion capture system) before it can be used for athlete monitoring in the field. When validated, this sensor setup could provide additional information with regard to athlete monitoring. This may help professionals in a daily sports setting to evaluate their training programs, aiming to reduce injury and optimize performance.

INTRODUCTION:

Team sports (e.g., soccer and field hockey) are characterized by alternating brief explosive actions such as high-intensity running or sprinting, with longer periods of less demanding activities like walking or jogging¹⁻⁶. Over the last decades, the physical demands of the game evolved with more distance covered at high speed and sprinting, faster ball speeds and more passes^{7,8}.

Athletes constantly train hard in order to maintain and improve their physical capacity to withstand the physical demands of the game. The correct application of a training stimulus in combination with sufficient recovery induces responses that lead to adaptation of the human body, improving fitness and performance⁹. On the contrary, an imbalance between a training stimulus and recovery can lead to prolonged fatigue and an undesirable training response (maladaptation), which increases the risk of injury in both professional and amateur team sport athletes¹⁰⁻¹³.

One of the major risks accompanied with high training and match stimuli are muscle strain injuries. Muscle strain injuries constitute more than a third of all time-loss injuries in team sports and cause more than a quarter of the total injury absence, with the hamstrings being the most

frequently involved¹⁴⁻¹⁷. Furthermore, the number of athletes that sustain a hamstring strain injury rises each year^{18,19}, despite that multiple programs have been introduced to prevent hamstring strain injuries^{12,13,20,21}. Consequently, this has a negative influence from sportive²² and financial²³ perspectives. Thus, adequate monitoring of individual athletes is essential for optimizing training schedules, minimizing injury risk and optimizing performance.

Current athlete monitoring practice in team sports is mainly based on position data measured by local or global positioning systems^{24,25}. These systems monitor activity with GPS-based metrics such as distance covered, average running velocity or accelerometry-based metrics such as PlayerLoad²⁶⁻²⁸. A disadvantage of these measures is that they do not include lower extremity kinematics. Optoelectronic measurement systems serve as a gold standard to perform a kinematic analysis of the lower extremities during a linear sprint²⁹⁻³². The disadvantages of these systems are a lack of ecological validity due to their restricted measurement area, the need of an expert to operate the system and the time consuming data analysis. Thus, this method is not suitable for daily sports practice.

Rapid development in sensor technology may overcome the limitations of current methods to monitor athletes. The recent reliability, miniaturisation and data storage possibilities of inertial measurement units (IMU) enables in-field application of sensor technology. IMUs contain an accelerometer, gyroscope and magnetometer which measure the acceleration, angular velocity and magnetic field, in three orthogonal axes respectively^{33,34}. With sensors securely fixed to body segments, sensor fusion algorithms and a biomechanical model, it is possible to estimate joint kinematics³³. The registration of joint kinematics in combination with information about the acceleration of different body segments may improve athlete monitoring in team sports.

By coupling the IMU sensor setup to a standardized field test, it can be illustrated how lower extremity kinematics are registered during linear sprinting in the field, which could be a useful measure for identifying injury-risk factors. The sensor setup could provide additional information to current monitoring measures that professionals may use for optimizing training schedules to improve performance and minimize injury risk. Therefore, the main purpose of this article is to demonstrate an inertial sensor setup for estimating hip and knee joint kinematics of team sport athletes in the field.

PROTOCOL:

All methods described in this section have been approved by the ethical committee of the Center for Human Movement Sciences of the University of Groningen (Register number: 201800904).

1. Field test and inertial measurement unit preparation

1.1. Set two cones at least 1 m from each other to determine the start of the field test.

NOTE: The 1-m distance between the cones enables the subject to run easily through the starting point of the field test. This distance can be adjusted to the preference of the test leader.

1.2. Determine the end point of the field test by rolling measuring tape from the starting point of the test until a 30-m linear distance has been travelled.

1.3. Set two cones at least 1 m from each other to determine the end point of the field test.

1.4. Prepare the IMUs to get properly attached to the subject's body.

NOTE: See **Table of Materials** for IMU dimensions and weight characteristics.

1.4.1. Cut stretch tape into 5 pieces the size of 10 cm x 10 cm.

1.4.2. Cut double-sided adhesive tape (e.g., toupee tape) into 5 pieces equal to the size of the IMUs that are used.

1.4.3. Attach a piece of double-sided adhesive tape to each IMU.

1.4.4. Label each IMU, so that it can be recognized individually during data analysis.

2. Subject preparation

2.1. Obtain information about the subject's gender, age, body weight, and height. Ask the subject to fill in a questionnaire about their background in team sports. Obtain written informed consent from subjects that meet the inclusion criteria.

NOTE: Examples of questions: (i) For how many years do you play soccer? (ii) At which level do you play soccer? (iii) How many hours per week do you have soccer training during the past 6 months? (iv) What is your playing position? (v) Did you experience any pain or did you sustain a musculoskeletal injury at the lower extremity during the past 6 months?

2.2. Determine if the subject meets the inclusion criteria.

NOTE: Include subjects when they did not experience any musculoskeletal injuries or pain in the lower extremities in the 6 months before executing the protocol; Subjects should have more than 1-year experience in competing team sports at amateur level.

2.3. Ask the subject to change into sports clothing (e.g., a soccer shirt, soccer shorts and soccer shoes).

NOTE: Because sensors will be placed on the tibia, soccer socks are unwanted.

2.4. Prepare the IMUs for attaching to the subject's body.

2.4.1. Align all 5 IMUs next to each other.

2.4.2. Activate all five IMUs at the same time by pushing a button on top of the sensor. The sensor is activated when a green light is blinking.

NOTE: From this moment, each IMU samples data at 500 Hz. Data is stored on a SD card internally. Data has to be uploaded to a laptop or computer after the test has been completed.

2.4.3. Ensure that a mechanical peak has been generated by tapping all IMUs on a hard surface at the same time (e.g., on a table).

NOTE: The mechanical peak is needed for synchronizing the IMU signals. Synchronization of the IMU signals is performed during data processing (section 5). This section is not necessary when commercially available sensors are used. In that case, use the corresponding software to synchronize the sensors.

2.5. Attach the IMUs to the subject's body (Figure 1).

2.5.1. Shave the subject's body hair at the following anatomical locations: at the sacrum between both posterior superior iliac spines, the anteromedial bony part of both right and left tibia, and the lateral part of both right and left thigh (i.e., tractus illiotibialis).

NOTE: The anatomical locations where sensors should be placed can be determined by palpation.

2.5.2. Spray adhesive spray on the anatomical locations described in step 2.5.1. Wait 5–10 s to make sure the adhesive spray is dry.

NOTE: Hold the spray at least 10 cm (4 inches) away from the skin and spray the desired area with a sweeping motion.

2.5.3. Remove the protective layer of the double-sided adhesive tape from the IMUs.

2.5.4. Place the IMU at the anatomical described anatomical locations. Write down the anatomical location with the corresponding label of the IMU (e.g., right shank: IMU 1).

2.5.5. Attach the stretching tape on top of each IMU to make sure the sensor is additionally secured to the skin.

3. IMU sensor calibration

3.1. Instruct the subject to stand still in a neutral position with their feet hip-width apart and their hands in their side. Maintain this position for a minimum period of 5 s.

3.2. Instruct the subject to flex their left hip and knee to a 90° angle in the sagittal plane followed by extending the hip to their neutral position as described in step 3.1.

NOTE: For definitions of kinematic variables, see **Figure 2**.

3.3. Repeat step 3.2 for the right hip and knee.

3.4. Instruct the participant to flex their trunk towards the ground and return to their neutral position.

3.5. Wait for a minimum period of 5 s.

3.6. Repeat steps 3.1–3.5 once.

4. Execute the 30-m linear sprint test

4.1. Instruct the subject to perform a warming up (e.g., the soccer specific FIFA 11⁺ warming up programme²⁰).

4.2. Inform the subject about the test protocol.

4.2.1. Clearly state that the risk of sustaining an injury during the test is not higher than during normal training and that the subject can abort the test at any time, without giving any reason.

4.2.2. Instruct the subject to stand in the correct starting position, with their preferred foot standing on the starting line and their shoulders behind the starting line on the field.

4.2.3. Instruct the subject that the test leader will count down from 3 to 0 followed by shouting 'Start'. Instruct that when 'Start' has been called, the test begins.

4.2.4. Inform the subject to sprint as fast as possible until the 30-m end point has been reached. After the 30-m finish point has been reached, the subject has to decelerate as fast as possible to a standstill position.

4.2.5. Allow the subject to ask questions. If needed, allow the subject to perform a practice run to familiarize the subject with the protocol.

4.3. Ask the subject if the instructions were clear.

4.4. Make sure the subject is in the correct starting position.

4.5. Count down from '3' to '0' and shout 'Start' to start the test. Start the timer when the start sign has been given.

4.6. Encourage the subject in order to achieve maximal performance.

265 4.7. Stop the timer when the participant has reached their standstill position.

267 4.8. Repeat steps 4.4–4.6 until three sprints have been performed.

269 NOTE: Let participants rest for at least 2 min between trials. Include the fastest sprint for data
270 analysis.

272 4.9. Instruct the subject to perform a cooling down.

274 4.10. Detach the IMUs from the subject by removing the stretch tape and double-sided adhesive
275 tape from the subject's body.

277 5. Data processing

279 5.1. Connect the IMU with a computer by using a USB cable. Export the raw IMU data to a specific
280 folder on the computer.

282 5.2. Open MATLAB (version r2018b). Import the raw IMU data files (i.e., accelerometer,
283 gyroscope and magnetometer data).

285 5.3. Synchronize the raw IMU data files.

287 5.3.1. Import the acceleration data file of one sensor (e.g., pelvis sensor).

289 5.3.2. Calculate jerk by differentiating the X, Y and Z acceleration signals. Sum up the X, Y, and Z
290 jerk to obtain the total jerk.

292 5.3.3. Obtain the mechanical peak by finding the index value in the data file where the total jerk
293 has reached its maximal value. The index value is the start of the measurement.

295 5.3.4. Delete all data points of the acceleration data, magnetometer data and gyroscope data
296 before the index value of the sensor.

298 5.3.5. Repeat steps 5.3.1–5.3.3 for each raw data file of the corresponding sensor.

300 5.3.6. Determine which sensor contains the lowest amount of data points by obtaining the
301 number of sampled data points for each data file.

303 5.3.7. Cut all other data files equal to the size of the sensor that registered signals for the shortest
304 time period.

306 5.4. Filter gyroscope data using a second order low-pass Butterworth filter with a cutoff
307 frequency of 12 Hz.

NOTE: The filter and particular cutoff frequency were chosen based on visual data inspection in previous pilot experiments.

5.5. Obtain sensor orientation with respect to the global earth frame by calculating the orientation quaternion of the sensor using a Madgwick filter³⁵.

NOTE: An extensive description of how sensor orientation with respect to the global earth frame is calculated is described in Madgwick et al.³⁵.

5.6. Align the sensor coordinate frame to body segment.

5.6.1. Select the index numbers of the data file when the subject was standing still during calibration (step 3.1).

NOTE: It is assumed that the longitudinal axis of the sensor is similar to the gravity vector.

5.6.2. Use the index numbers of step 5.6.1 to calculate the average orientation of each sensor with respect to the global reference frame during the static calibration. Then rotate the sensor frame of each sensor, so that it aligns with the global reference frame during static calibration.

5.6.3. Select the index numbers of the data file when the calibration movement of the left leg was performed (step 3.2).

5.6.4. Rotate the orientation of the left leg sensors in such a way that the calibration movement is a rotation about the frontal axis only.

5.6.5. Repeat steps 5.6.3 and 5.6.4 for the calibration movements of the right leg and trunk.

5.7. Obtain joint orientations by expressing the orientation of the distal body segment in the coordinate frame of the proximal segment for each joint.

5.8. Obtain joint angles by decomposing the obtained joint orientations into 'XZY' Euler angles.

NOTE: How to decompose the obtained joint orientations into 'XZY' Euler angles is described in the work of Diebel³⁶.

5.9. Obtain joint angular velocities expressing the gyroscope signals of each distal segment in the coordinate frame of its corresponding proximal segment minus the angular velocity of the proximal segment.

5.10. Identify each step during the linear sprint by using a step detection algorithm.

5.10.1. Import the filtered gyroscope data in MATLAB.

5.10.2. Use a peak detection function to identify peaks in the gyroscope signal.

NOTE: Peak height was set at $286.5^{\circ}\cdot s^{-1}$ and minimal peak distance was set at 100 samples (= 0.2 s).

5.11. For each step, calculate the maximum value for hip angle, knee angle, hip angular velocity, and knee angular velocity.

5.12. For each step, calculate the minimum value for hip angle, knee angle, hip angular velocity, and knee angular velocity.

5.13. For each step, calculate the hip range of motion by subtracting the minimum hip angle from the maximum hip angle.

5.14. For each step, calculate the knee range of motion by subtracting the minimum knee angle from the maximum knee angle.

6. Data analysis

6.1. Import the processed IMU data in MATLAB.

6.2. Divide the sprint into an acceleration, a top speed and deceleration phase based on the steps identified by the step detection algorithm.

NOTE: Sprint phases in this article were chosen arbitrarily. The acceleration phase is defined as step 3 to 8³⁷, whereas the deceleration phase is defined as the last eight steps of the sprint. Top speed data was derived from steps performed between these phases.

6.3. Select the angular velocity data for data analysis.

6.4. Calculate the mean values and standard deviation of the kinematic variables of all steps during each phase of the 30-m linear sprint test.

6.5. Repeat step 6.3 and 6.4 for the angle data.

REPRESENTATIVE RESULTS:

Five subjects (all male; all soccer players; age 22.5 ± 2.1 years; body mass 77.0 ± 3.8 kg; height 184.3 ± 5.2 cm; training experience 15.3 ± 4.8 years) performed a maximal 30-m linear sprint. Hip angles ranged between $100.5^{\circ} (\pm 8^{\circ})$ maximal flexion and $183.1^{\circ} (\pm 8^{\circ})$ maximal extension during acceleration, $104.1^{\circ} (\pm 8^{\circ})$ maximal flexion and $195^{\circ} (\pm 8^{\circ})$ maximal extension during top speed, and $128.4^{\circ} (\pm 11^{\circ})$ maximal flexion and $171.9^{\circ} (\pm 23^{\circ})$ minimal flexion during deceleration. Hip angular velocities ranged between $744.9^{\circ}\cdot s^{-1} (\pm 154^{\circ}\cdot s^{-1})$ and $-578^{\circ}\cdot s^{-1} (\pm 99^{\circ}\cdot s^{-1})$ during acceleration, $802.6^{\circ}\cdot s^{-1} (\pm 192^{\circ}\cdot s^{-1})$ and $-674.9^{\circ}\cdot s^{-1} (\pm 130^{\circ}\cdot s^{-1})$ during top speed, and $447.7^{\circ}\cdot s^{-1} (\pm 255^{\circ}\cdot s^{-1})$ and $-430.3^{\circ}\cdot s^{-1} (\pm 189^{\circ}\cdot s^{-1})$ during deceleration.

Furthermore, knee angles ranged between $73.5^{\circ} (\pm 12^{\circ})$ maximal flexion and $162.6^{\circ} (\pm 7^{\circ})$ minimal flexion during acceleration, $62.8^{\circ} (\pm 12^{\circ})$ maximal flexion and $164.8^{\circ} (\pm 6^{\circ})$ minimal flexion during top speed, and $81.1^{\circ} (\pm 16^{\circ})$ maximal flexion and $168.6^{\circ} (\pm 12^{\circ})$ minimal flexion during deceleration. Knee angular velocity varied between $935.8^{\circ}\cdot s^{-1} (\pm 186^{\circ}\cdot s^{-1})$ and $-1137.8^{\circ}\cdot s^{-1} (\pm 214^{\circ}\cdot s^{-1})$ during acceleration, between $1155.9^{\circ}\cdot s^{-1} (\pm 200^{\circ}\cdot s^{-1})$ and $-1208.2^{\circ}\cdot s^{-1} (\pm 264^{\circ}\cdot s^{-1})$ during top speed, and $1000.1^{\circ}\cdot s^{-1} (\pm 282^{\circ}\cdot s^{-1})$ and $-1004.3^{\circ}\cdot s^{-1} (\pm 324^{\circ}\cdot s^{-1})$. **Figure 3** illustrates continuous kinematic data of one trial of the linear 30-m sprint test, whereas **Figure 4** and **Figure 5** illustrate kinematic data of one stride cycle during acceleration, top speed and deceleration of one trial.

FIGURE LEGENDS:

Figure 1: Representation of sensor placement. (A) Sensor placement on the right and left shank. (B) Sensor placement on the pelvis, and right and left thigh.

Figure 2: Definitions for hip and knee joint angles and angular velocities. (A) Representation of the neutral position in the sagittal plane. Joint angles in neutral position are 180° . (B) Representation of hip joint (θ_{hip}), knee joint (θ_{knee}) and range of motion (ROM).

Figure 3: Visualization of sprint kinematics of one trial during accelerating, top speed and decelerating phase. An asterix indicates when a step has been detected. (A) Left and right hip flexion and extension angles over time. (B) Left and right hip angular velocities over time. (C) Left and right knee angles over time. (D) Left and right knee angular velocities over time.

Figure 4: Polar plot in which hip joint angle ($^{\circ}$) and angular velocities (flexion/extension) of one step are illustrated during one during acceleration, top speed and deceleration.

Figure 5: Polar plot in which knee joint angle ($^{\circ}$) and angular velocities (flexion/extension) of one step are illustrated during acceleration, top speed and deceleration.

DISCUSSION:

Current methods to monitor athletes in team sports do not register lower extremity kinematics, which could be a useful measure for identifying injury-risk factors. The gold standard for analysing lower extremity kinematics during sprinting are optoelectronic measurement systems²⁹⁻³². Although optoelectronic measurement systems serve as a gold standard, these systems lack ecological validity due to their restricted measurement area. The sensor setup presented in this article overcomes the limitations of the current measurement systems, and is relatively cheap. The possibility to register lower extremity kinematics in the field, measured by the sensor setup, may improve athlete monitoring practice.

Previous studies that examined sprint kinematics^{29,31,37-39} reported hip angles ranging from 210° extension to 90° flexion. Furthermore, these studies reported knee angles ranging from 160° minimal flexion and 40° maximal flexion. The values observed in this study show a similar trend.

One study³⁸ reported hip angular velocities ranging from $-590^{\circ}\cdot\text{s}^{-1}$ to $700^{\circ}\cdot\text{s}^{-1}$ and knee angular velocities ranging from $-1,000^{\circ}\cdot\text{s}^{-1}$ to $1,100^{\circ}\cdot\text{s}^{-1}$. Although the values observed in this study were higher, they show a similar trend over time. It should be mentioned that the current method has not been validated yet, which is a limitation of the current study. Results should therefore be interpreted with caution. Future research should validate the sensor setup with a gold standard, such as a valid optoelectronic measurement system, before the sensor setup can be used for athlete monitoring in the field.

The current study has some limitations that need to be addressed. First, apart from the characteristics of the IMUs that have been used, users must be aware that the signals derived from the IMUs are affected by several sources of error which limit the possible range of applications⁴⁰. First, the oscillation of the soft tissues around the bones (i.e., soft tissue artefacts⁴¹) can affect the registration of kinematics. For this reason, it is important to carefully attach the IMUs to the subject's body according to the steps described in the protocol. Although necessary steps were undertaken, it should be noted that the current study did not include extra elastic straps to prevent erroneous sensor movement. This could improve results and may be seen as a limitation of this study. Second, ferromagnetic disturbances from other devices (mainly inside buildings) change the magnitude or direction of the measured magnetic field vector of the IMU's magnetometer, thus causing errors in estimated orientation⁴². Therefore, sources of ferromagnetic disturbance should be avoided as much as possible. Moreover, it must be noted that the sensor setup is not applicable to sliding tackles since the sensors will detach from the skin as a result of making contact to the ground surface. Thus, participants should be instructed not to perform sliding tackles during small sided games. A possible solution for this problem could be to integrate the sensor setup in smart garments (i.e., a Smart Sensor Tights).

The kinematic variables obtained by the sensor setup could be used in a segmental model in order to monitor athletes in the field. Previous research found reduced maximum combined hip flexion and knee extension angle (i.e., theoretical hamstring length) after each half of a soccer match simulation⁴³. In the same study, an increase in shank angular velocity has been observed during the ends of each half. The lower hamstring length combined with an increased shank velocity may indicate an increased risk of excessive hamstring strain after fatigue. Such alterations in sprinting kinematics may be detected in a field setting using an inertial measurement unit (IMU) driven segmental model. Besides changes in joint kinematics, forces that act on the body as a whole can be estimated as well. Ground reaction forces (GRF) describe the biomechanical loading experienced by the total musculoskeletal system, and can be estimated using Newton's second law of motion (i.e., $F = m \cdot a$). Current research in running used GRF estimation to optimize sprint performance^{44,45} or assessing potential injury risk⁴⁶⁻⁴⁹. These studies suggest that loading rates, vertical impact force peaks and horizontal braking force are related to musculoskeletal overuse injuries. Although it is a challenge to estimate GRF accurately during highly dynamic team-sport specific movements^{50,51}, the possibility to monitor these variables during measurements on the field could provide new information to optimize performance, or to prevent injuries.

The results presented in this paper are limited to monitoring lower extremity kinematics during

a linear sprint, focussing on hamstring strain injury mechanism. However, it should be noted that hip and groin injuries also occur frequently in team sports^{14,17,52-54}. These injuries are probably caused by repetitive involvement of kicking and change of direction. Thus, future research should not only limit their focus on sprinting in relationship with the hamstring strain injury mechanism but also focus on expanding knowledge regarding change of direction tasks⁵⁵ and kicking⁵⁶⁻⁵⁸ in relationship with hip and groin injuries.

To conclude, this sensor setup could be integrated in smart garments. Smart garments may enable to register lower extremity kinematics in the field during team sport specific tasks, which could improve monitoring athletes in the future. This may help professionals in a daily sports setting to evaluate their training programs and optimize them, aiming to reduce injury risk.

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The authors have nothing to disclose.

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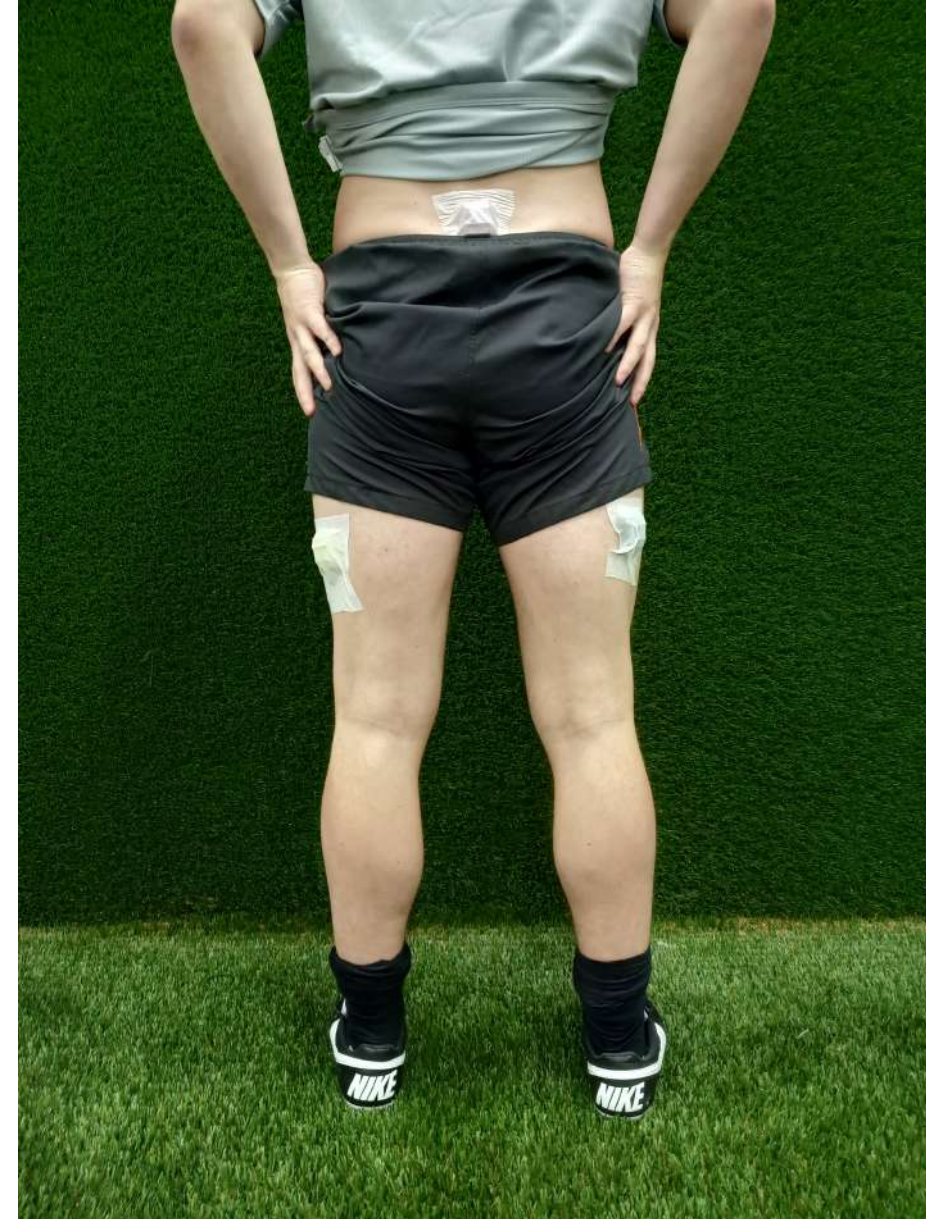
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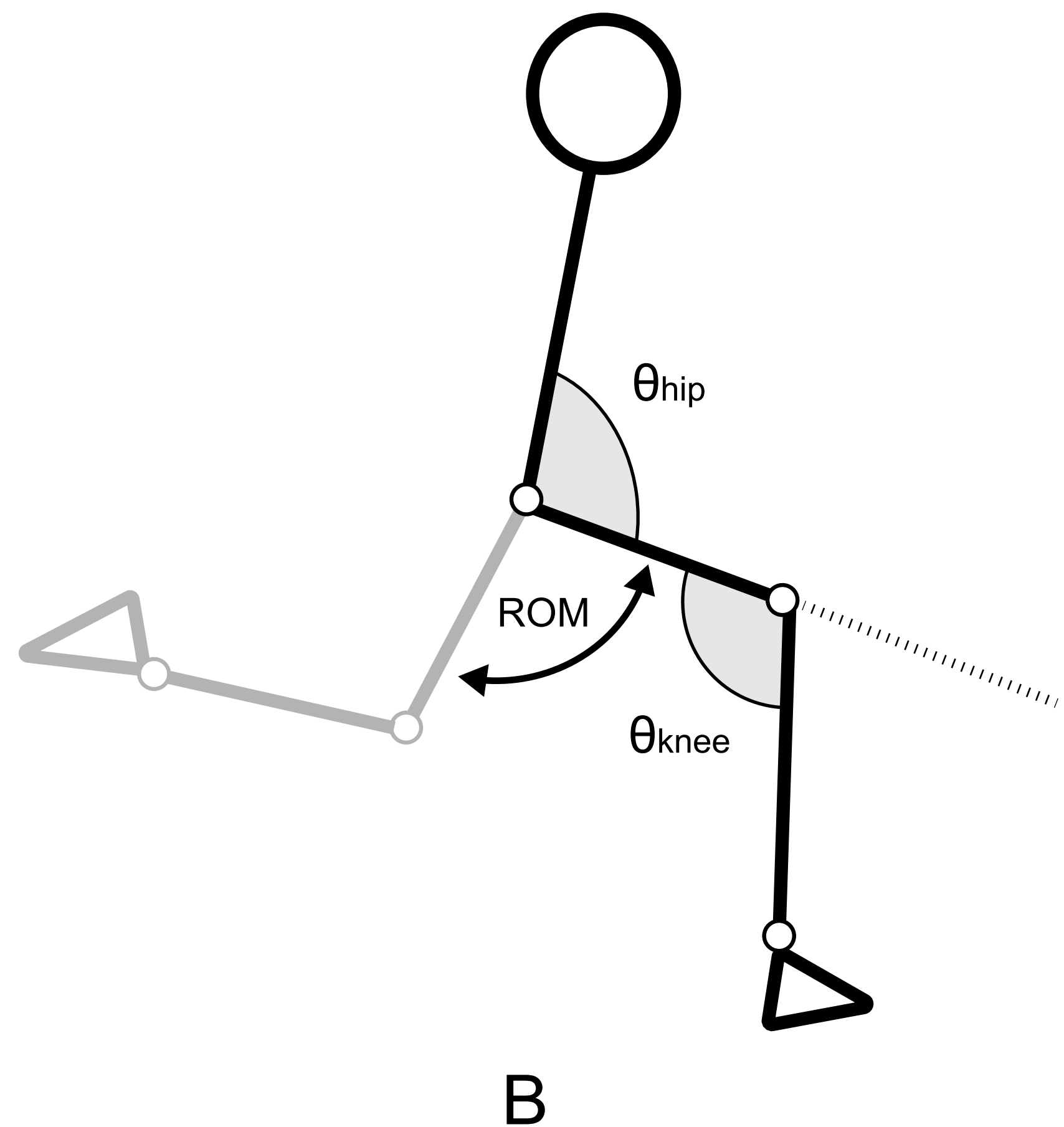
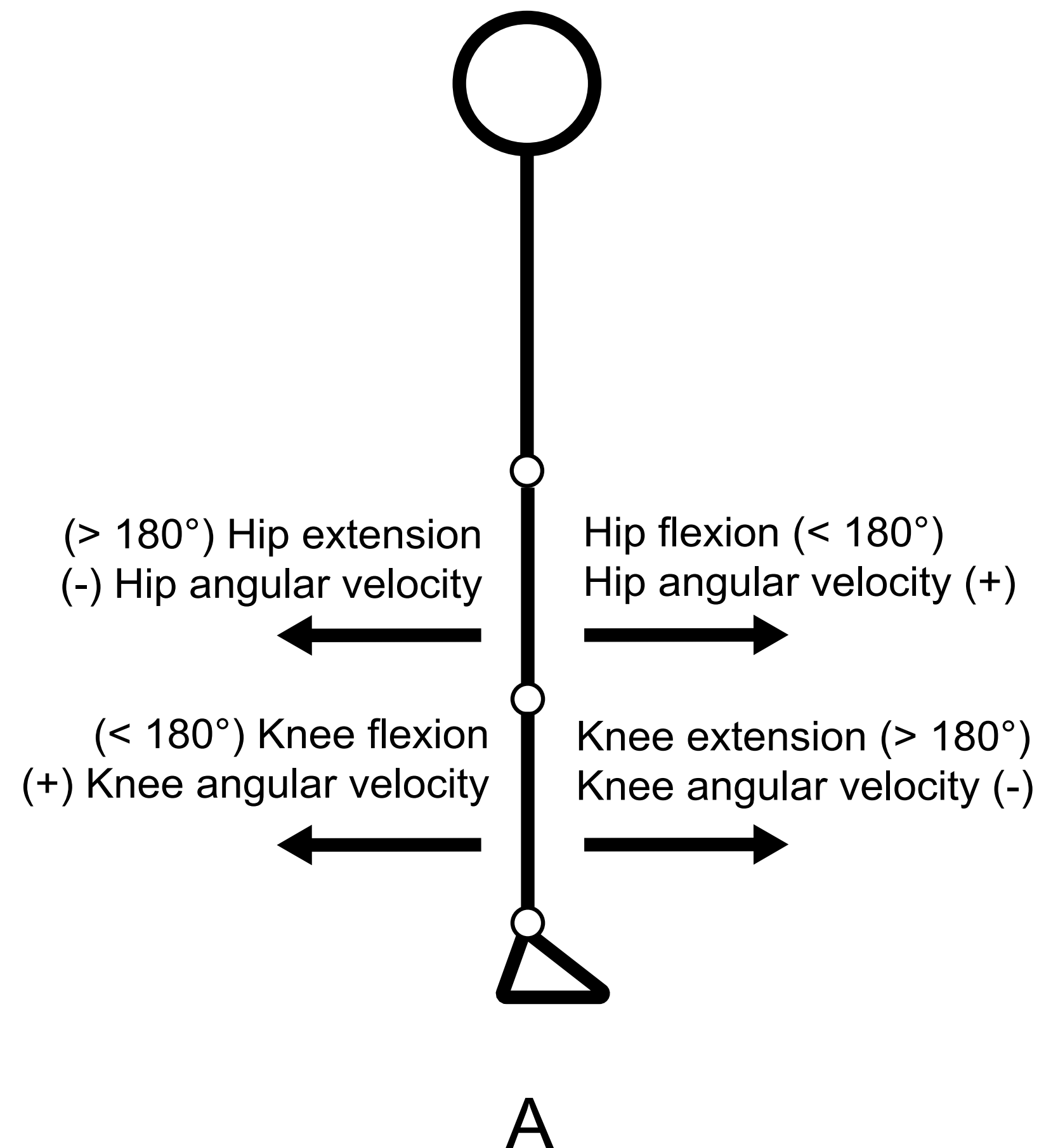


A



B

Figure 2: Definitions for hip and knee joint angles and angular velocities.



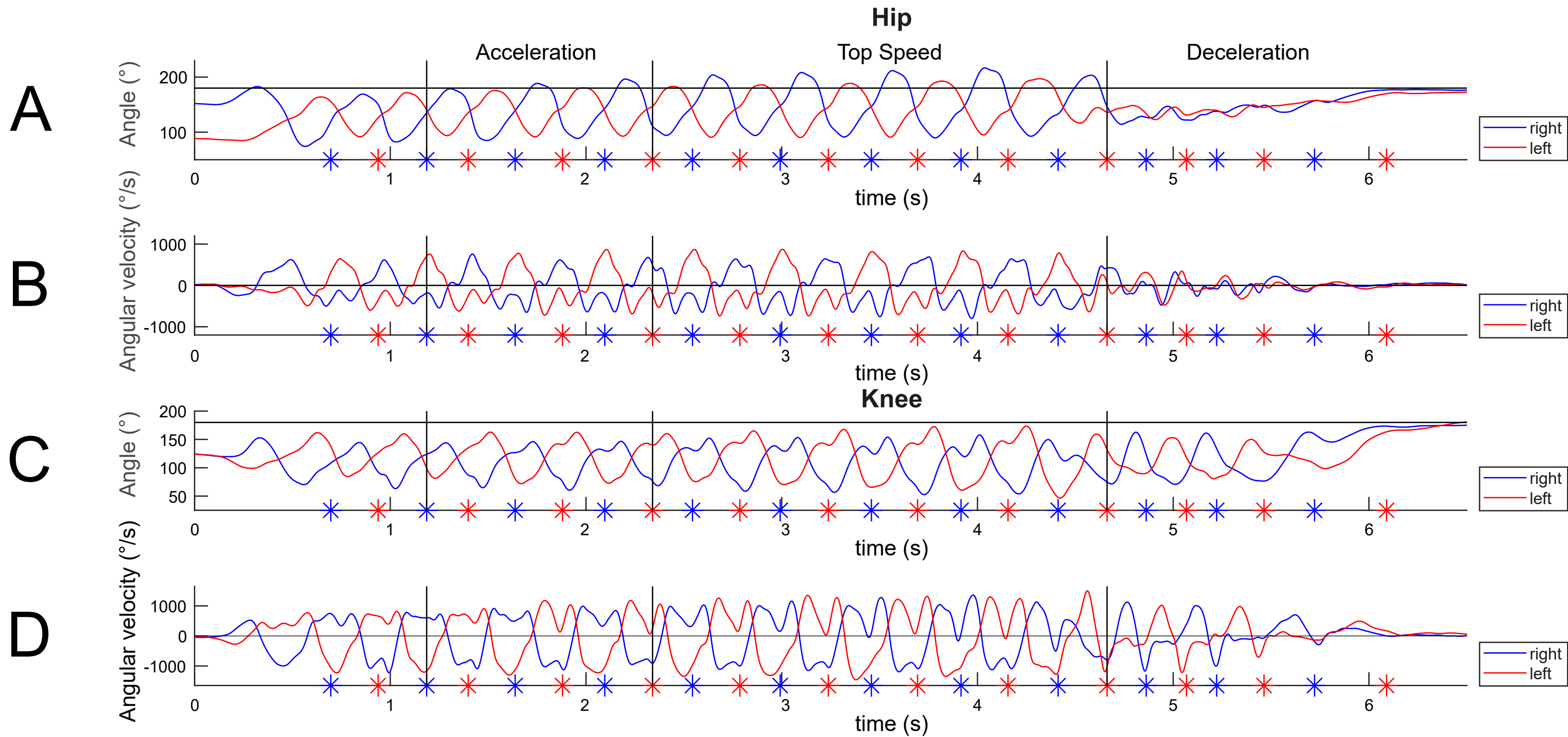
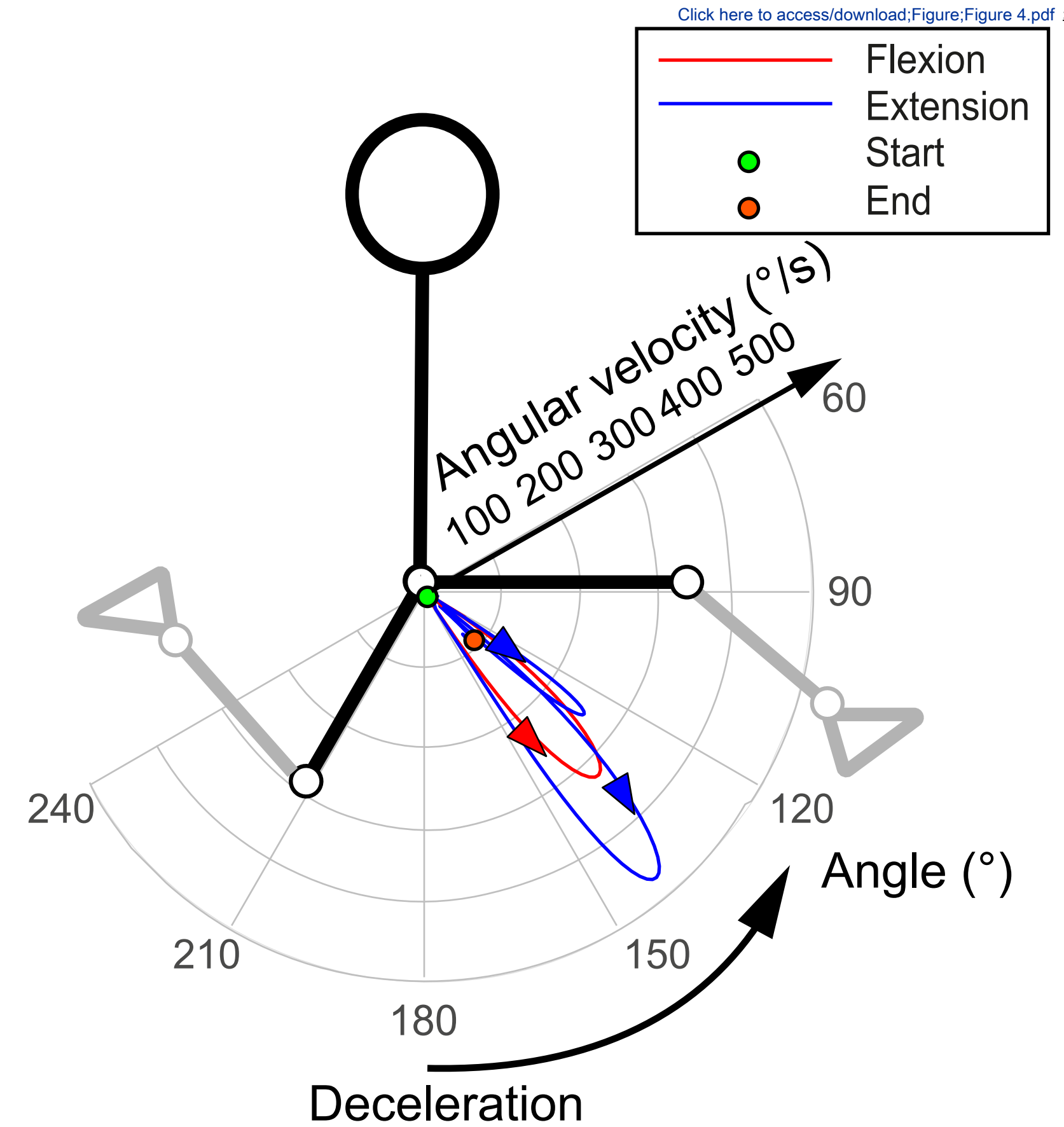
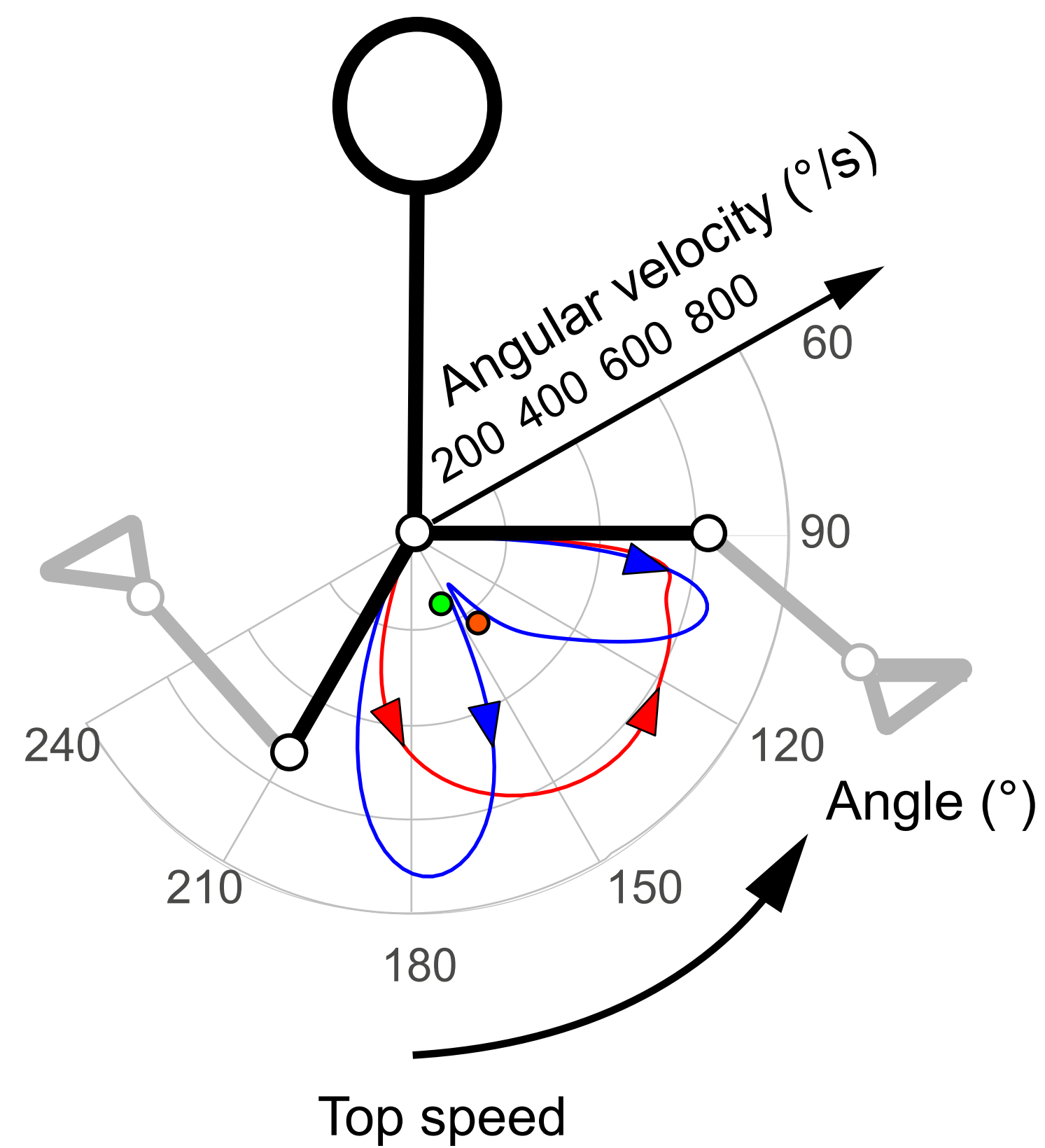
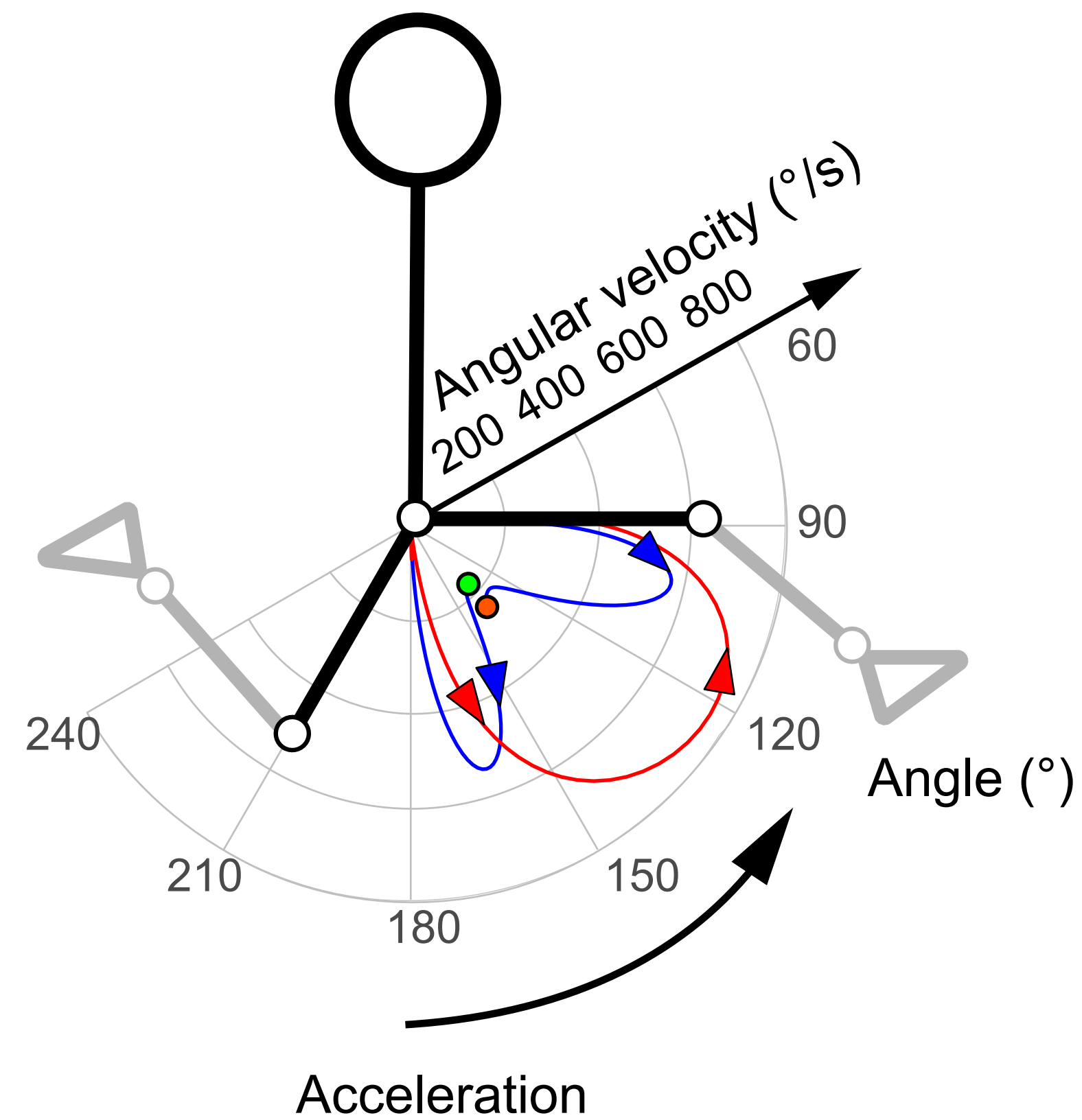
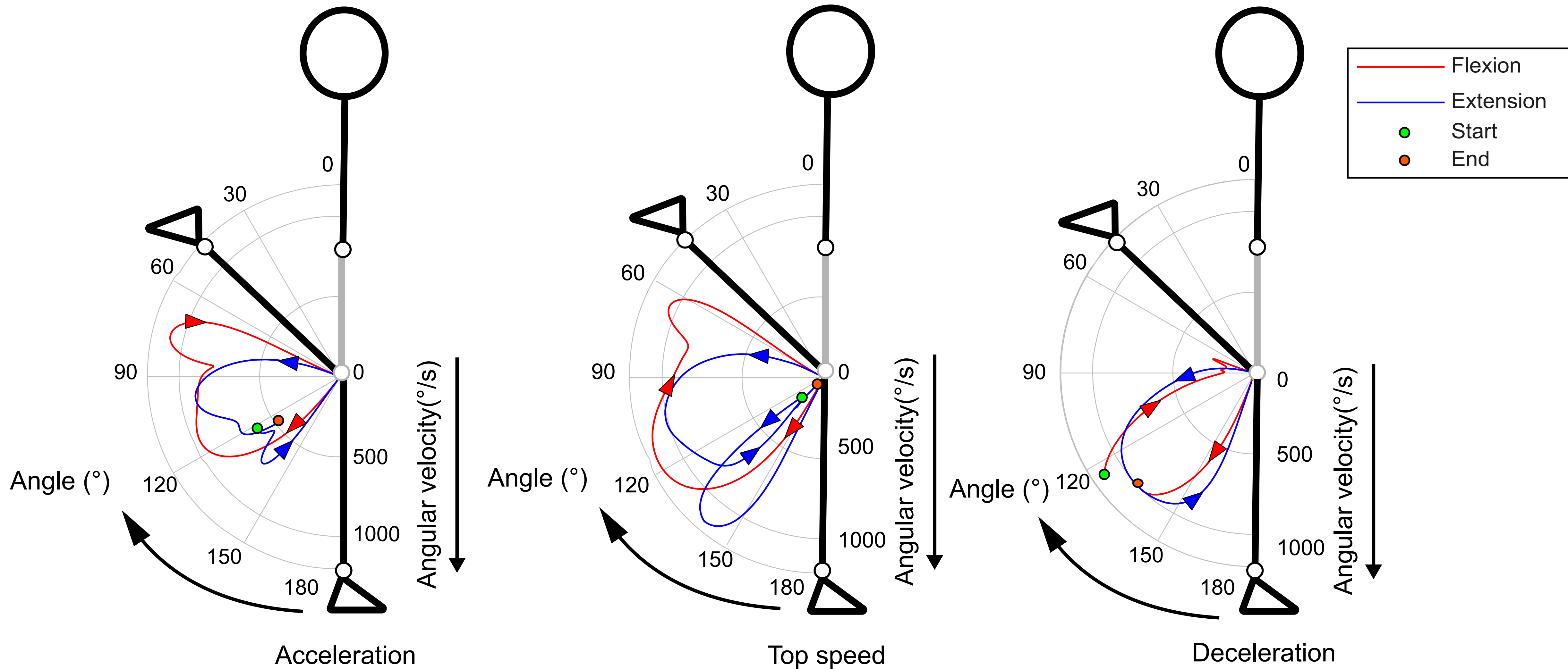


Figure 4: Polar Plot Hip





Name of Material/Equipment	Company	Catalog Number
Computer software	The MathWorks, Inc., Natick, MA, USA	
Cones	Nike	
Double-sided adhesive tape		
Inertial Measurement Units	MPU-9150, Invensense, San Jose, California, United States	
Measuring tape		
Pre-tape spray	Mueller Tuffner, Mueller Sports Medicine, Inc., Wisconsin, United States	
Stretch Tape	Fixomull, BSN Medical, Almere, The Netherlands	

Comments/Description

Matlab Version 2018b

n = 4

For attaching IMUs on the skin

n = 5; Dimensions: 3.5 x 2.5 x 1.0 cm; Weight: 0,011 kg; Sample frequency: 500Hz; Accelerometer: ± 16 G, Gyroscope: ± 2000 °/s

Minimal length: 30 meters

Contents: 283 g

Rebuttal Letter

4th of December 2019

Revisions required for your JoVE submission JoVE60857R1 - [EMID:cdbb73f3c316977f]

Xiaoyan Cao
Review Editor
JoVE

Dear Dr. Cao,

Hereby you receive the revised manuscript: "A novel inertial measurement unit based method to estimate hip and knee joint kinematics in team sport athletes on the field".

We thank the reviewers for their constructive comments that helped us to further improve the quality of the manuscript. As requested, we addressed the reviewer's comments point by point and highlighted adjustments in the manuscript using track changes (pages and line numbers refer to the track changes manuscript).

We are looking forward to hearing from you again.

Yours sincerely, also on behalf of all co-authors,

Bram Bastiaansen,
Center for Human Movement Science, University Medical Center, University of Groningen,
Groningen, the Netherlands.
Email Address: b.j.c.bastiaansen@umcg.nl

Reviewers' comments:

Reviewer #2:

A novel inertial measurement unit based method to estimate hip and knee joint kinematics in team sport athletes on the field.

Summary

I would like to thank the authors for their clearly communicated replies and substantial work in revising their work. They have done a rigorous revision of their manuscript and have adequately addressed the majority of my previous comments. However, I would like the authors to consider the minor comments below before accepting this paper for publication.

Author's reply: We would like to thank the reviewer for their additional comments, which we feel further improve the manuscript.

Specific comments

Abstract

1. L55-56 This sentence mentions the use of IMU for different purposes and states that "... it is possible to estimate joint kinematics." If it is already known that joint kinematics can indeed be estimated (based on previous observations), it seems odd that the present study investigates the potential for using IMUs to estimate knee and hip joint kinematics, as stated in the next sentence. Suggest rephrasing to tone down or leaving out completely.

Author's reply: We have rephrased "it is possible to estimate joint kinematics" into "joint kinematics could be estimated".

Changed: Line 56-57

2. L64 Delete "yet".

Author's reply: Changed accordingly, Line 66.

3. L65 "... gold standard". Please check the manuscript for a consistent use of the term.

Author's reply: In the manuscript the terms "golden standard" and "gold standard" were used to describe the best available measurement tool. The correct term should be gold standard and therefore all terms "golden standard" were changed to "gold standard" in the manuscript.

Changed: Line 67, Line 439, Line 454

4. L66 As highlighted in my previous review, a validation of the accuracy and precision of the proposed method is required by comparing it against a gold standard method for measuring hip and knee joint kinematics. I would therefore suggest using a more generic term for a gold standard to compare the present method to instead (e.g. "motion capture system"). 'Vicon' is the merely the name of a company that provides hard- and software solutions for motion capture purposes (amongst others) and a reference to a company in the context of this sentence is somewhat inappropriate.

Author's reply: We agree with the reviewer and therefore have changed "e.g. Vicon" into "e.g. a valid optoelectronic motion capture system".

Changed: Line 67-68.

Author's reply: Furthermore, we have removed the reference to the company named Vicon in the discussion section of the article.

Removed: Line 455-456.

5. L66-68 To refer to the proposed method as a means to monitor "training load" is inappropriate. Please see the third major concern in my review for the previous version of the manuscript and rephrase appropriately.

Author's reply: We agree with the reviewer that the proposed method is not used for monitoring load. Instead, the proposed method could be used for monitoring athlete's kinematics in the field. Therefore, we adjusted all statements referring to load monitoring into statements referring to athlete monitoring.

Summary

Changed: Line 44: “Monitoring athletes.....”.

Changed: Line 45-46: “Current methods to monitor athletes do not include the lower extremities.”

Changed: Line 47-48: “Attaching multiple inertial measurement units monitoring athletes in the field.”

Abstract

Changed: Line 51: “Current athlete monitoring practice.....”

Changed: Line 68: “Future research should validate can be used for athlete monitoring in the field.”

Changed: Line 70: “When validated, this sensor setup with regard to athlete monitoring.”

Introduction

Changed: Line 95: “Thus, adequate monitoring of individual athletes ...”

Changed: Line 99: “Current athlete monitoring practice in team sports...”

Changed: Line 110: “Rapid development in sensor technology ... to monitor athletes.”

Changed: Line 116-117: “The registration of joint kinematics ... may improve athlete monitoring in team sports.”

Discussion

Changed: Line 437: “Current methods to monitor athletes.....”

Changed: Line 444: “... may improve athlete monitoring practice.”

Changed: Line 456: “... before the sensor setup can be used for athlete monitoring in the field.”

Changed: Line 477: “... In order to monitor athletes in the field.”

Changed: Line 505: “... which could improve monitoring athletes in the future.”

6. L66-68 Likewise, carefully reconsider the use of "training load" in the introduction section (e.g. L102, 108), as well as when using the phrase throughout the rest of the manuscript. The authors define training load as "intensity, duration and frequency", none of which are quantified or described by the kinematic behaviour of the knee and hip joint.

Author's reply: We have used the term “training load” to introduce the reader to the process of adaptation needed for improving performance. Coaches can vary their training schedules (intensity, duration and frequency) in order to give their athletes a certain stimulus that leads to adaptation if an appropriate balance between the stimulus and recovery is applied. Eventually, this improves athlete performance. The proposed method could be used as a tool for evaluating the stimuli provided during training and optimizing training schedules. We agree with the reviewer that the term “training load” is a distracting term for describing a training stimulus and therefore we have changed all references to training load to “training stimulus”.

Changed: Line 82: “The correct training stimulus in combination with”

Changed: Line 84-85: “... an imbalance between a training stimulus and recovery”

Changed: Line 89: “One of the major risks with high training and match stimuli”

Introduction:

7. L72 "... high-intensity running ... ".

Author's reply: Changed accordingly, Line 75

8. L93-94 Distance covered, average running velocity and PlayerLoad are not kinematic variables but GPS or accelerometry-based metrics. Suggest rephrasing.

Author's reply: We have rephrased the sentence into “These systems monitor activity with GPS-based metrics such as distance covered, average running velocity or accelerometry-based metrics such as PlayerLoad”

Changed: Line 100-102

9. L102-109 If training load is defined as "intensity, duration and frequency", how can measuring joint kinematics improve "load monitoring" in team sports? See my comment for L66-68 above.

Author's reply: We agree that monitoring joint kinematics cannot be used as a measure for monitoring load. We therefore have removed the term training load from the manuscript and

changed that to athlete monitoring. Furthermore, we do not define training load but refer to the application of training stimuli in combination with sufficient recovery to enhance the process of adaptation. We refer to point number 5 & 6 for changes made in the manuscript.

Methods

10. L276 Include how the IMU was connected to the computer (e.g. via a wire, Bluetooth).

Author's reply: The IMU is connected with the computer using a USB-cable. We therefore have added "by using a USB-cable" to the corresponding sentence.

Changed: Line 287

11. L279 "a software environment" is too generic. Specify what software was used specifically and provide details such as software version, developer etc.

Author's reply: We have used MATLAB (version r2018b; The MathWorks Inc., Natick, MA, USA) for importing and processing the raw IMU data files. We have added these details of the software version the first time MATLAB has been mentioned in the manuscript. Thereafter, we only have mentioned MATLAB in the manuscript.

Changed: Line 290: we have changed "a software environment" into "MATLAB (version r2018b; The MathWorks Inc., Natick, MA, USA)".

Changed: Line 292: we have changed "Import the raw in the computer software environment" into "Import the raw.... in MATLAB".

Changed: Line 361: we have changed "the software environment" into "MATLAB".

Changed: Line 382: we have changed "a computer software environment suitable for data analysis" into "MATLAB".

12. L301 Since the gyroscope data is used to determine joint angles, signal filtering directly affects the calculated kinematic outcomes. Please provide some rationale and/or references on why this particular filter and cut-off frequency were chosen.

Author's reply: Data is filtered with a low-pass second order Butterworth filter with a cutoff frequency of 12 Hz to reduce the effects of soft tissue artefacts around impact with the ground. The filter and particular cut-off frequency were chosen based on visual inspection of the data in previous pilot experiments in the project. We have added this information as a note in step 5.4 of the manuscript.

Changed: Line 315, “..... second order low pass Butterworth filter”.

Changed: Line 318 & 319, “NOTE: The filter and particular cut-off frequency were chosen based on visual data inspection in previous pilot experiments.”

13. L343, 364 See my comment for L279 above.

Author's reply: We changed “software environment” into MATLAB.

Changed: Line 361 & Line 382

Discussion:

14. L418-425 Consider my previous comments on load and kinematics for L66 and L102 above.

Author's reply: We have considered the previous comments on load and kinematics. We refer to comments 5, 6 and 9 for the changes made in the manuscript.

Changed: Line 437: “Current methods to monitor athletes.....”

Changed: Line 444-445: “The possibility to register lower extremity kinematics ... may improve athlete monitoring practice.”

15. L420 "... gold standard ..."

Author's reply: Changed accordingly, Line 439.

16. L435 See my comment for L66.

Author's reply: We have removed the reference to the company named Vicon, see also point 4.

Removed: “(e.g. Vicon, Oxford Metrics Ltd., Oxford, United Kingdom)”, Line 455-456.

17. L436 Consider my previous comments on training load monitoring for L66 and L102 above.

Author's reply: We have considered the previous comments on training load monitoring. See also points 5, 6, 9 and 14.

Changed: Line 456: "... before the sensor setup can be used for athlete monitoring in the field."

Changed: Line 477: "... In order to monitor athletes in the field."

Changed: Line 504: "... which could improve monitoring athletes in the future."

18. L455 "a model" is quite generic term. Please include some more specifics of the type of model the authors are alluding to.

Author's reply: We use a segmental model that could be used for analysis of kinematic variables of the lower extremity. Therefore, we have added the word "segmental" to model.

Changed: "The kinematic variables obtained by the sensor setup could be used in a segmental model....", Line 476-477.

19. L458 "... increase ..."

Author's reply: Changed accordingly, Line 480.

20. L485 Delete reference to performance optimisation, as this has not been discussed or justified previously.

Author's reply: Changed accordingly.

Removed: "and optimize performance", Line 507

Reviewer #3:

Manuscript Summary:

The authors introduce the topic of IMUs for kinematics measurement well, the advantage over optoelectronic measurement systems and how this protocol relates to movements carried out in team sports. The steps listed in the procedure are clear (bar a couple of suggestions listed under minor concerns) and all required materials and equipment are listed, enabling others to repeat this testing method. The results obtained are comparable to other

studies carried out previously (some using different protocols and conditions) but have not been validated by a gold-standard system, which the authors readily acknowledge. Other limitations are also discussed - one I believe to be fairly significant is the fact that the current sensor set up does not allow for sliding tackles. Wearables are advantageous because they can be unobtrusive and so should not impact the movement of users. Any information the authors have on how long subject preparation takes or subject comfort with the sensors would be an interesting point of discussion. In general, the protocol is well thought out and the authors are able to demonstrate the impact of this type of research in aiding injury prevention.

Author's reply: We would like to thank the reviewer for the valuable input. Below, we have provided a point-by-point response. We believe the manuscript has been improved because of it.

Major Concerns:

None

Minor Concerns:

1. Additional information that would be useful to include in the protocol is how much rest is taken between each trial (4.8 line 265).

Author's reply: Participants rested at least two minutes between trials. We have added this information within the NOTE corresponding to the section mentioned.

Changed: "Let participants rest for at least two minutes between trials.", Line 277.

2. Please provide additional information about the order of the Butterworth filter used for data processing (5.4 line 301).

Author's reply: We have used a second order Butterworth filter for data processing. We added this information to the manuscript. See also comment 12 of reviewer #2 addressing a similar issue.

Changed: “Filter gyroscope data using a second order low-pass Butterworth filter....”, Line 315.

3. I would suggest moving the NOTE on table of materials (line 169) to below 1.4 (line 136) as this is the first mention of IMUs and gives an indication earlier on of the dimensions needed for the double-sided adhesive tape.

Author’s reply: We have moved the NOTE on table of materials to below 1.4.

Changed: Lines 178-179, “NOTE: See table of materials for IMU dimensions and weight characteristics.”, have been moved to section 1.4 (Line 144-145).

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Author(s):	Bram J.C. Bastiaansen, Erik Wilmes, Michel S. Brink, Cornelis J. de Ruiter, Geert J.P. Savelsbergh, Annemarijn Steijlen, Kaspar M.B. Jansen, Frans C.T. van der Helm, Edwin A. Goedhart, Doris van der Laan, Riemer J.K. Vegter, Koen A.P.M. Lemmink

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