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Wearable Technology in Biomechanics and S.T.E.M. Education

xsens

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About the Author

Dr Jason Konrath obtained his PhD in Biomechanics with Griffith University, as well as a degree in Exercise and Health Science with the University of Western Australia. He has an extensive background in both research and fitness coaching in a variety of elite sports from all over the world. He was previously the Scientific Advisor for the Indian men's hockey team, strength and conditioning coach with West Australian Rugby, and has advised many other sporting teams across hockey and football. He has a proven track record of exercise prescription to improve conditioning, strength and power, speed and agility, movement competencies and rehabilitation for elite performance and injury prevention.

Jason is an expert in Biomechanics and has published his research in many top tier Biomechanics and Sports Medicine Journals. He is the recipient of awards from the International Society of Orthopaedics and Traumatology, the Asia Pacific Knee Arthroscopy and Sports Medicine Society, and the European College of Sports Science. Jason has a strong background in sensor-based motion capture having previously worked with Xsens Technologies as the Product Manager of 3D Body Motion. In addition to this, he is an expert in musculoskeletal modelling, using computational models to estimate muscle forces and joint contact forces during human locomotion.

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1 Theoretical Framework

1.1 Inertial measurement units

Motion capture as the name suggests, involves any method of capturing motion for the purpose of analysing human or object movement. Such analyses provide a range of applications spanning from medical applications, sport, ergonomics, military applications and entertainment just to name a few.

There are many different methods of motion capture that span both optical and non-optical methods. 2D video analyses have been used as an easy way to evaluate critical variables and enhancing communication between coaches and players. However, these methods also have the disadvantage of being misleading when viewed out of plane, as the footage only represents the particular plane of view it was filmed from. This has led to 3D motion analysis techniques including opto-electronic and retro-reflective systems. These systems have a high degree of precision and accuracy, however can lack ecological validity. This has given rise to inertial measurement units, which show great promise in terms of its accuracy, as well as having strong ecological validity from being in the user's natural environment.

1.1.1 Components of an IMU

Recent times have given birth to the inertial measurement unit (IMU). IMU's are a collection of measurement tools that capture data about the device's movement. Each IMU contains 3D accelerometers, 3D gyroscopes and 3D magnetometers, each being a Micro-Electro-Mechanical-System (MEMS). Below is a description of each component.

3D Accelerometers
An accelerometer is a device that measures accelerations, or the change of velocity (speed) with respect to time. Your mobile phone for instance contains accelerometers and can sense motions or vibrations. Accelerometers consist of a mass-spring system contained within a vacuum. As an acceleration occurs, this causes displacement of the mass in the mass-spring system, which is measured. It is important to note, that to measure a devices free acceleration, the acceleration due to gravity must be removed.

3D Gyroscopes
A gyroscope is a device that measures orientation about one plane, as well as angular velocity (rate of turn). It can also provide stability to reference directions in navigation systems. Gyroscopes contain a spinning wheel or disc that track rotations or twist. A tiny oscillating mass is suspended in a spring system, from which rotations exert a force perpendicular to the direction of motion and to the axis of rotation. When the mass is further away from the axis of rotation, the force is larger. The mass receives a different reading either side of the oscillation, which registers a measure for the rate of turn.

3D Magnetometers
A magnetometer is a device that measures the direction and strength of a magnetic field at a given location. Much like the workings of the needle of a compass, it can be used to inform heading or direction along the ground plane of the earth. However, the direct use of magnetometers to estimate heading may be prone to errors due to magnetic distortions from nearby metallic objects.

1.1.2 Sensor fusion and estimation of orientation

Individual sensor orientation data can be obtained by fusing the signals obtained from the constituent sensors into a sensor fusion framework, these may be complementary filters or Kalman filters[1]. Orientation refers to a description of how an object is positioned in space, not to be confused with its location, but rather how it is directed. The location and orientation together explain how an object is placed in space. Typically, orientation is given relative to a reference frame and specified with a cartesian coordinate system. Changing the orientation of a rigid body is the equivalent of rotating the axes of a reference frame attached to it.

Sensor orientations may be estimated by combining the sensor readings of the accelerometer and magnetometer. The accelerometer can be used as a measure of inclination due to the gravity vector, much like the workings of a water level. While the magnetometer can be used as a measure of heading, much like the workings of a compass needle. Short term changes in orientation may be accurately tracked by the gyroscope, while adding the acceleration and magnetometer signals can provide long term stability[2]. It is worth noting, inclination has potential to be distorted from long-term accelerations, while heading has potential to be distorted from the presence of ferrous materials.

Given that gyroscopes measure the rate of turn or the angular velocity, we know from angular kinematics that angular velocity is the first derivative of angular displacement with respect to time. Therefore, integration over time (t) of the angular velocity (ω) measured by the gyroscope can give an estimate of the change in orientation (q). That is

$$q(t) = \int_0^t \omega \, dt + \omega_0$$

However, this orientation change is prone to integration drift over time. It is the addition of gravitational and magnetic information from the accelerometer and magnetometer respectively that gives stabilising information in the long term[3].

Given that accelerometers measure linear accelerations, we know from linear kinematics that acceleration is the first derivative of velocity (v) and that velocity is the first derivative of displacement. Therefore, if the sensors free acceleration (a) (where the gravity vector has been removed) is double integrated over time (t), the change in position can be estimated. That is

$$v(t) = \int_0^t a \, dt + v_0 \quad and \quad p(t) = \int_0^t v \, dt + p_0$$

This will provide accurate predictions of the relative position change for short periods of time, however will inherently drift over time, due to both sensor errors and orientation estimate errors.

A rigid body in 3 dimensions can have its orientation described in several ways. The two ways we most commonly work with are Euler angles and quaternions. Euler angles give the orientation by three successive rotations in a sequence called roll, pitch and yaw. This representation is often the most intuitive and most easily visualised, however, when calculating joint angles, it can suffer from gimbal lock, which occurs when two axes are driven into a parallel configuration, resulting in no available rotation about the other axis. For this reason, quaternions or rotation matrices are preferred for calculations of joint angles, with Euler angles used for interpretation. Quaternions are an efficient, non-singular description of 3D orientation, the normalised quaternion is represented as a vector q= <q_0, q_1, q_2, q_3> with q_0 being the real component, and q_1, q_2, q_3 being the complex or imaginary parts[4]. This format has mathematical advantages, however for visualisation and easy interpretation of 3D angles, quaternions are often converted back to Euler angles following calculations.

1.1.3 Coordinate systems

All kinematic data are expressed with respect to a global origin, or an earth fixed coordinate system. This reference is defined with a right-hand Cartesian coordinate system, in which

- The x axis is positive moving forward lying in the horizontal plane referenced to magnetic North.
- The y axis is pointing lateral lying in the horizontal plane, orthogonal to the x axis and z axis, according to the right-hand rule.
- The z axis is lined along the vertical, referenced to gravity and positive when pointing up.

Figure 24: Coordinate system of an inertial sensor

Rotating about the x axis will give us the roll orientation, rotating about the y axis will give us the pitch orientation, while rotating about the z axis will give us the yaw orientation. The yaw orientation is also referred to as heading, with the direction of the earths magnetic field used as a reference for the calculation of 3D orientation. However, due to this fact, ferromagnetic objects in close proximity within the environment may cause distortions to the magnetic field. A magnetically homogenous environment refers to an environment where there are no ferromagnetic objects to distort its signals. However, the Xsens XKFcore algorithm[1] has the ability to compensate for errors caused by temporary disturbances by using other available sensors information along with valid assumptions. These algorithms become more difficult as disturbances last longer.

1.1.4 Joint angles

To describe human motion measurement and relate it to anatomical definitions, such as joint angles, it becomes necessary to define a coordinate reference frame for the respective body segment. The coordinate axes of each segment is then aligned with respect to the global origin during calibration. The standardisation for joint coordinate systems is based upon recommendations of the International Society of Biomechanics

(ISB), in accordance with descriptions of Wu and Cavanagh (1995)[5], Wu et al. (2002)[6] and Wu et al. (2005)[7]. For most segments of the body, an origin of the reference and direction of axes are defined based on the positions of bony landmarks, from which opto-reflective markers are typically placed.

It is important to note, that we do not measure positions of anatomical landmarks as we do with optical measurement systems. We take measurements of relevant points as an indication for the scaling of segment lengths. We then use measured accelerations, angular velocities and rotations applied to segments of an underlying anatomical model to estimate positions.

A calibration or alignment pose can be used to allow a sensor to segment calibration[3], whereby the direction of the axes of each segment can be determined. This pose is usually a neutral pose in which all of the joints are in a neutral or zero posture which we refer to as n-pose or T-pose, depending on how the arms are placed. The origin of a segment is always the proximal joint centre which becomes the functional rotation point. The child segment moves relative to the parent segment. All segments are assumed to be rigid bodies with no translation occurring. The relationship between the orientation of each segment and its corresponding sensor ${}^{BS}q$ can be determined from the following equation

$${}^{GB}q = {}^{GS}q \otimes {}^{BS}q^{*}$$

Where ${}^{GB}q$ is the orientation of the segment with respect to the global frame, ${}^{GB}q$ is the orientation of the of the sensor with respect to the global frame, $\otimes$ represents the quaternion multiplication, and * represents the complex conjugate of the quaternion. A joint rotation is then defined by calculating the difference between the orientation of the distal segment ${}^{GB2}q$ and proximal segment ${}^{GB1}q$ by

$${}^{B1B2}q = {}^{GB1}q^{*} \otimes {}^{GB2}q$$

Following this Euler angles can be extracted from this. The ISB Euler angle extractions are typically done with a Z component corresponding to flexion/extension, an X component corresponding to abduction/adduction and a Y component corresponding to internal/external rotation[8]. The quaternion processes just described are for those wanting a method of calculating angles across a range of rotations.

It is also possible to calculate a single angle between the longitudinal axes of two segments using vectors along with the dot product using the following formula

$$v_1 \cdot v_2 = |v_1||v_2| \cos{(\alpha)}$$

We know the Dot product of two vectors (v_1 and v_2) gives the product of the vector magnitudes and the cosine of the angle (α) between them.

1.2 Biomechanics

1.2 What is Biomechanics

Biomechanics is a field examining the external and internal forces acting on the human body (or for any biological organism for that matter), as well as the effects produced by these forces. As the name suggests, it integrates components of mechanics with biology and therefore requires an interdisciplinary approach. In essence, mechanics encompasses the laws of motion first introduced by Sir Isaac Newton and has laid the foundation for how we describe both forces and motion mathematically. Parallel to this, the study of human biology examines humans through the complex interplay of many fields, the most important for biomechanics being functional anatomy, physiology and neuroscience. Biomechanics is applied to a range of different personas encompassing sport, clinical and workplace to name a few. However, despite the user case, it involves similar processes and outcomes.

1.2.1 Types of Biomechanics

Sports Biomechanics

Biomechanics when applied to sport has the ability to optimise performance and mitigate risk of injury, as well as aid the development of innovative equipment and designs. Fundamental to undertaking these processes and achieving these outcomes requires precise measurement, which has gone hand-in-hand with the development of technologies.

Figure 1: Analysing the push off the blocks of an Olympic curler

Clinical Biomechanics

Clinical biomechanics focuses on medical and clinical applications to support clinicians to explain causes of musculoskeletal disorders. Further it allows methods to support diagnosis, prognosis and evaluation of treatment methods and technologies. This may provide valuable knowledge to clinicians to improve clinical management of a patient.

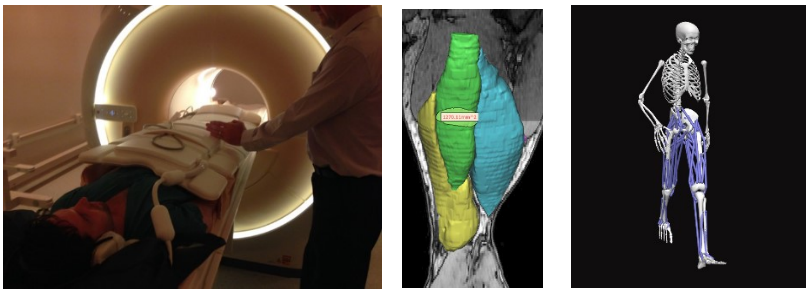


Figure 2: Using MRI of a patient to determine effects of hamstring atrophy on gait from Konrath et al. (2016)[9]

Workplace Biomechanics
Biomechanics in the workplace aims to optimise design, products or work processes by analysing the way people interact with their environment. To achieve this, one must understand the postures and movements undertaken by the worker. The goal of this should be to reduce human error, improve productivity, as well as improve safety and comfort to the worker. This has the potential to help companies and their employees to undertake their work activities so that performance can be improved, whilst reducing the risk of work-related injury.

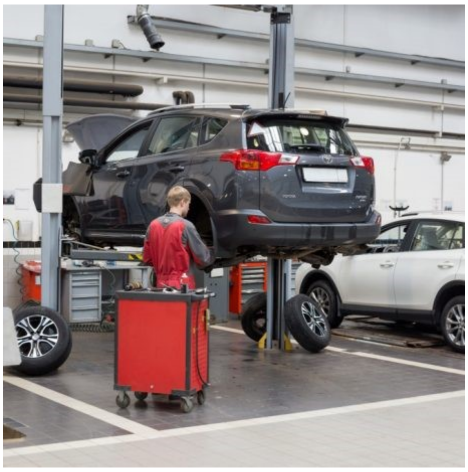


Figure 3: Analysing a worker's postures in the workplace

1.2.2 Biomechanical approach to motion analysis

There is an essential process to the biomechanical analysis of a task or skill, that requires a systematic approach, whether it be qualitative (without measurement) or quantitative (with measurement). This process is undertaken in 5 compulsory phases done in an ordered fashion with each step proceeding the other. These phases are known as preparation, observation, evaluation/diagnosis, intervention and re-observation. The flow of this process is shown below.

Figure 4: Biomechanical approach to motion analysis

Preparation
This is where we first prepare to investigate the task or skill, by understanding the movement of interest. We must understand the movement, such that if we modify anything, will it improve performance, or mitigate the risk of sustaining an injury. This involves breaking down and identifying the different phases of movement in the task/skill, as well as identifying the critical variables involved in each phase.

Observation
This is where we determine how to observe the critical variables of interest. What is the correct plane of movement or degree of freedom we need to analyse, is it about the frontal plane, the sagittal plane or the transverse plane. Further, if video footage needs to be recorded, this requires the cameras field of view to be set up perpendicular to the plane of interest. We are also required to determine which stage or phase of movement to perform our observation, and any critical event (such as during ball or ground contact etc.). Moreover, we must determine when we would like to perform the observation with respect to time, such as during the early stages of training or a match, versus later stages, when we may be examining the effects of fatigue.

Evaluation or diagnosis
This involves measurement of the critical variables of interest at the relevant time points. We must also compare what is observed to what it should be, which may also differ across age and skill levels. This allows us to assess the strengths or weaknesses of the given task/skill, as well as prioritise the weaknesses to be addressed systematically.

Intervention
Once we have established the characteristics of the critical variables of interest, we may now intervene and attempt to modify them for the purpose of improving performance or mitigating injury risks. This may involve the following types of changes:

- Technical: This may involve changes to the technique of the task/skill
- Physical: This may involve improving the physical aspects of the task/skill by addressing a given weakness via appropriate strength or conditioning training.
- Psychological: Addressing any potential psychological fears towards a task or skill, this may be present returning from injury.

Re-observation
This is the fifth and final step from which the task/skill is re-observed to investigate whether the required modifications have been achieved. This can again be either qualitative or quantitative to assist in assessing the performance outcomes.

1.2.3 Different levels of biomechanical analysis

Depending on what the critical variables of interest are, there may be different levels of analysis that are required to be performed. Each of these levels requires particular tools or methods to be performed. It may involve kinematic analysis, kinetic analysis or musculoskeletal analysis, each of which will be discussed in the subsequent sections, briefly

Kinematic analysis
Within Physics and Engineering disciplines, kinematics is the field of mechanics that describes the motion of points and objects without consideration of the forces that act on them.

Kinetic analysis

Within Physics and Engineering disciplines, kinetics is the branch of mechanics that deals with the causes of motion, more specifically forces and torques.

Musculoskeletal analysis

Assessing the action of individual muscle forces and joint contact forces requires a musculoskeletal modelling approach. Advancements in computational models have led to the development of specific algorithms to estimate these forces[10,11].

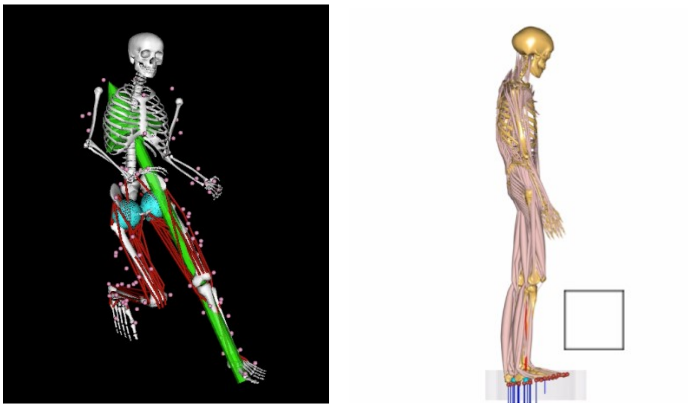


Figure 4: Computational musculoskeletal models can assess individual muscle forces and joint contact forces. OpenSim[10] (left) and AnyBody Technology[11] (right) are two such examples

1.3 Functional Anatomy

1.3.1 Anatomical planes

In order to describe human movement, we appoint hypothetical planes to transect the body, which allow us to define the direction of movements. We use three principle planes in anatomy which are referred to as the sagittal plane, the coronal plane and the transverse plane. Think of a plane as an imaginary flat surface that passes through the body. If we imagine a human standing upright, the sagittal plane is a plane parallel to the sagittal suture passing through the midline of the body, dividing it into left and right sides. The coronal plane or frontal plane divides the body into posterior (back) and anterior (front) sections. While the transverse or axial plane divides the body into superior (above) and inferior (below) sections.

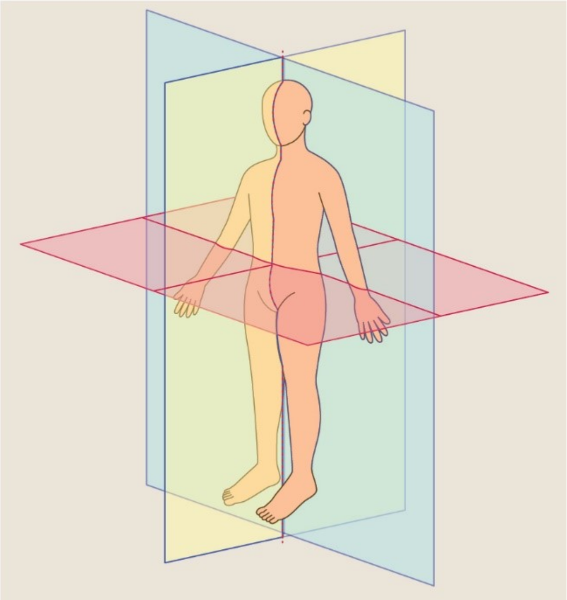


Figure 5: The anatomical planes of the body

1.3.2 Anatomical movements

Human movement occurs with the skeletal muscles of the body contracting and moving the bones of the skeletal system. Furthermore, these contractions can facilitate maintenance of posture and stability of joints. The joints between bones allow movement to take place with the range of motion influenced by factors such as the structure of the bones and the type of joint it forms (ball and socket, hinge joint, saddle joint etc.), the orientation and placement of ligaments, muscle size and muscle attachment points, as well as flexibility. The origin and insertion points describe the attachment points of the muscle on the bone, with the insertion point typically moving toward the origin point when the muscle contracts.

With respect to terminology of movement. In most cases, flexion refers to a decrease in a given joint angle and occurs in the sagittal plane, while extension creates an increase in the respective joint angle. Abduction refers to moving a given segment away from the midline of the body and occurs in the coronal plane, while adduction refers to moving the respective segment toward the midline of the body. Internal rotation refers to the rotation of a given segment toward the center of the body and occurs in the transverse plane, while external rotation refers to rotation of the respective segment away from the center of the body. It is worth noting that these are the most general movements, joint specific movements also exist, such as dorsi-flexion and plantar flexion for the ankle, pronation and supination at the elbow, as well as lateral bending and axial rotation for the spine, neck and head. Complex movements may also exist, such as circumduction, which refers to moving a segment in a circular motion, this involves the sequential combination of flexion, adduction, extension and abduction at a joint such as performing arm circles.

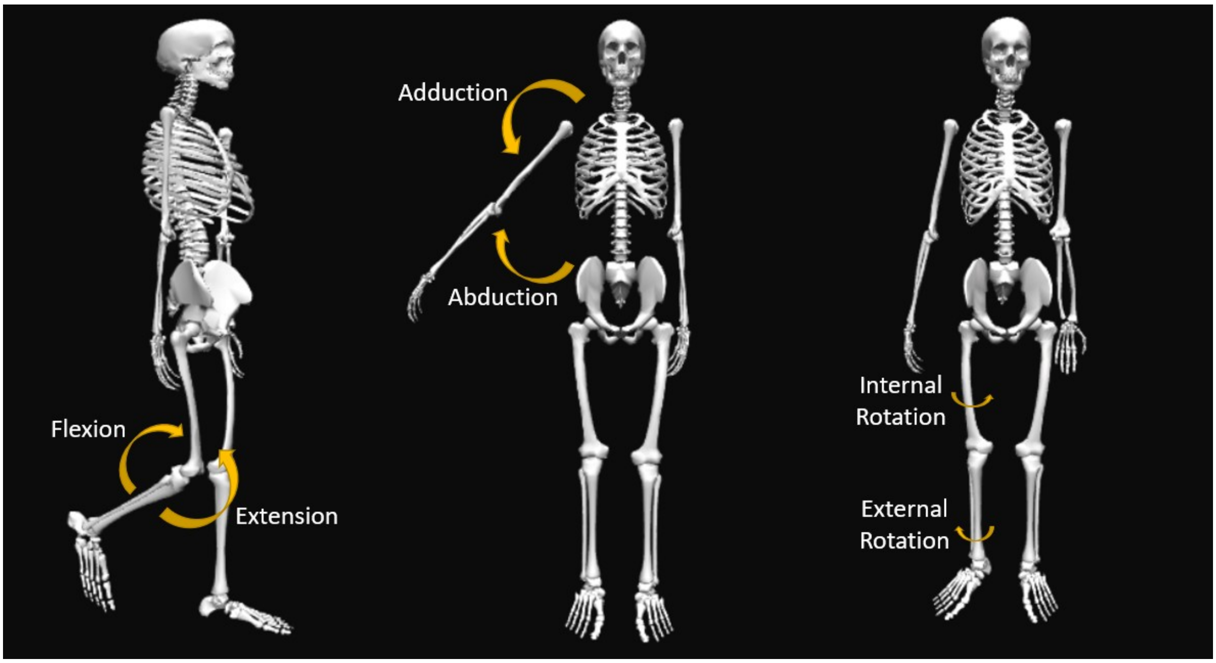


Figure 6: The different anatomical movements of the body's segments, shown in OpenSim[10]

The following table presents a simplified description of which muscles contribute to the respective movements of the lower body.

Muscle(s)	Anatomical movement
Quadriceps	Knee extension Hip flexion
Hamstrings	Knee flexion Hip extension
Hip flexors (Iliopsoas)	Hip flexion
Gluteus maximus	Hip extension
Gluteus medius	Hip abduction
Adductor group	Hip adduction
Calves	Plantar flexion (standing on tip toes)
Tibialis anterior	Dorsi flexion (curling toes up toward you)

The following table presents a simplified description of which muscles contribute to the respective movements of the upper body.

Muscle(s)	Anatomical movement
Pectorals	Shoulder adduction Shoulder internal rotation Shoulder flexion
Latissimus dorsi	Shoulder extension Shoulder adduction Shoulder internal rotation
Rotator cuff (external)	Shoulder external rotation
Deltoid	Shoulder flexion (anterior fibers) Shoulder adduction (anterior fibers) Shoulder abduction (medial fibers) Shoulder extension (posterior fibers) Shoulder abduction (posterior fibers)
Biceps	Elbow flexion
Triceps	Elbow extension
Wrist flexors	Wrist flexion
Wrist extensors	Wrist extension
Abdominals	Trunk flexion Trunk rotation
Erector spinae	Trunk extension

A simplified figure of the various muscle groups of the body is presented below, to help understand how they produce the described movements.

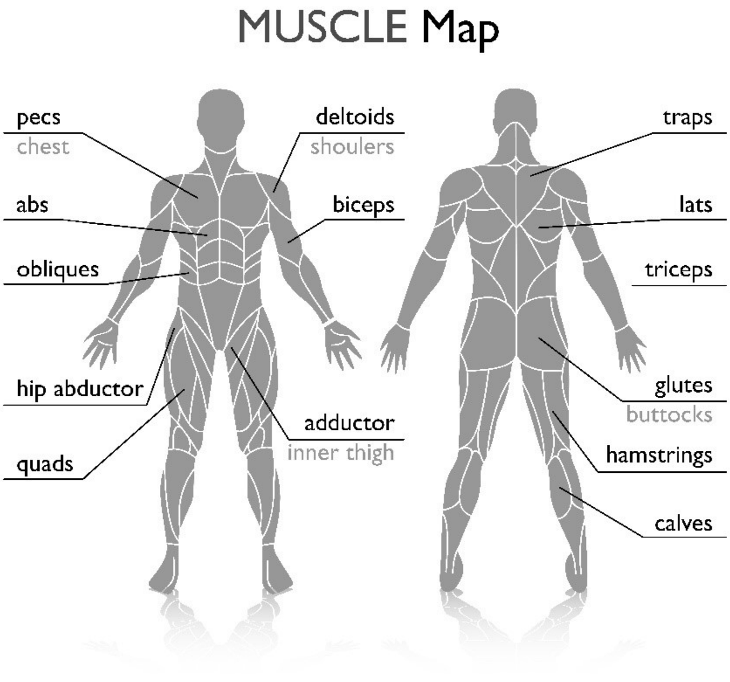


Figure 7: The various muscle groups of the body

1.4 Kinematics

1.4.1 General

Kinematics is the field of mechanics that describes the motion of points and objects without consideration of the forces that act on them. As we mentioned in the approach to motion analysis, kinematics can be either qualitative or quantitative. Qualitative analysis is a non-numerical description of motion based on observations with the naked eye. Quantitative analysis enables movement to be analysed numerically based on measurements of data. The advantage of quantitative analysis is that it provides an objective and accurate representation of movement, allowing one to quantify movements that may not be possible to capture with the naked eye. There are two ways to classify movement, which we refer to as linear motion and angular motion.

- Linear motion describes motion along a line which is either rectilinear (straight path) or curvilinear (curved trajectory). Such movements can be represented as either the body as a whole, in which we generally use the hip representing the bodies centre of mass; or, the endpoint of a segment, such as the path traced by the foot during a kick.
- Angular motion refers to rotary motion about an axis. With respect to human movement, we can think about this as the movement of body segments about a joint. When the angular motion of a number of body segments is combined, this produces linear motion of either the body or of a terminal segment.

Consider a soccer player approaching a penalty kick. He would first initially run up to the ball, producing linear motion of the hip. Then his upper leg would undergo angular motion relative to the hip, while his lower leg would undergo angular motion relative to the upper leg. The final velocity of the ankle which impacts with the ball, will be the combination of the linear motion of the hip, the angular motion of the upper leg with respect to the hip and the angular motion of the lower leg with respect to the upper leg.

Figure 8: What motions contribute to the final velocity of the ankle before ball-strike

1.4.2 Linear motion

Motion includes many components including position, distance, speed and acceleration velocity and acceleration, in the scalar form (without direction). While in the vector form (with direction), we refer to these as position, displacement, velocity and acceleration. All of these quantities are related to one another, with respect to time, and can be expressed mathematically.

Position refers to the location of an object or point in space. Distance is the total length of the path travelled between two positions (scalar), while displacement is the length and direction in a straight line between two positions (vector). Velocity describes how fast we move through the displacement between positions with respect to time (vector), while speed describes how fast we move through the distance between positions with respect to time (scalar).

Velocity (v) can be related to displacement (s) with respect to time (t) with the following equation

$$v = \frac{s}{t}$$

Or if plotted as a displacement-time curve, the derivative of displacement with respect to time, with the velocity being the first derivative of displacement.

$$v = lim \frac{\delta s}{\delta t} \; as \; \delta t \to 0$$

Acceleration describes how we increase or decrease velocity/speed with respect to time. Acceleration (a) can be related to a final velocity (v) and initial velocity (u) with respect to time with the following equation

$$a = \frac{v - u}{t}$$

Or if plotted as a velocity-time curve, the derivative of velocity with respect to time, with acceleration being the first derivative of velocity or the second derivative of displacement

$$a = lim \frac{\delta v}{\delta t} \; as \; \delta t \to 0$$

1.4.3 Angular motion

Angular motion refers to rotation, or motion about a fixed point or axis. In human movement it may involve the whole body, such as in a gymnasts' somersault or localised to a particular body segment, such as the movement of adjacent bones connected at a joint. Nearly all human motion comprises rotation of body segments, with the segments rotating about the joint centres that form their respective axis of rotation.

In geometry, an angle is defined as two lines sharing a common endpoint called the vertex. When we relate this to human movement and in a biomechanical sense, the longitudinal axis of two adjacent bones can be represented as two lines, with the vertex being the instantaneous joint centre. In angular motion we use particular units to measure angles, these units are degrees, radians or revolutions. A circle which describes as one revolution or rotation, contains 360 degrees, or 2π radians. The degree is the most commonly used and understood. However, in biomechanics, the radian is the most appropriate, as it is dimensionless. The radian is defined as the angle from which the length of the circles arc is equal to its radius, the number of radians can be calculated by dividing the arc length by the radius

$$\theta = \frac{arc\ length}{radius\ length}$$

To convert an angle in degrees to radians, you can multiply the angle in degrees by $\frac{\pi}{180}$, this is because the circumference of a circle is equal to 2πr, therefore 360 degrees is equal to 2π radians. Similarly, you can convert an angle in radians to degrees, by multiplying by $\frac{180}{\pi}$.

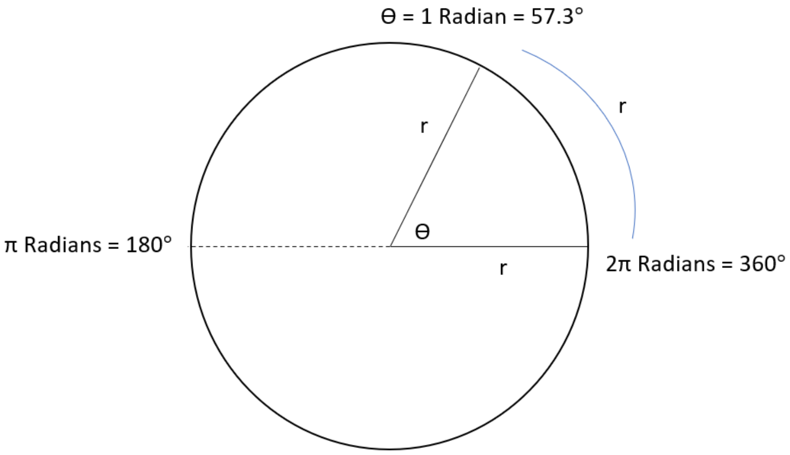


Figure 9: The radian, the angle the length of a circles arc is equal to its radius

For vector notations, the direction or polarity of the vector is determined by the right-hand rule. This is performed by placing the curled fingers along the direction of rotation with the vector defined as an arrow that coincides with the direction of the extended thumb. Conventionally, in the sagittal plane, segments moving anti-clockwise have a positive polarity, while segments moving clockwise have a negative polarity.

Similar to linear distance and displacement, angular distance (scalar) refers to the total angular change along its total path, while angular displacement (vector) is the difference between the final position and initial position about the axis of rotation. That is

$$\Delta\theta = \theta_{final} - \theta_{initial}$$

Angular speed is the angular distance covered with respect to time measured as a scalar quantity, while angular velocity (ω) is a vector quantity that determines the change of angular position with respect to time.

$$\omega = \frac{\theta_{final} - \theta_{initial}}{t}$$

Angular speed and angular velocity can be presented in degrees per second, however if further calculations need to be performed, the units must be in radians per second, as it is dimensionless. If plotted on an angular position-time curve, angular velocity can be calculated as the first derivative of angular position

$$\omega = lim \frac{\delta\theta}{\delta t}\ as\ \delta t \to 0$$

Using the right-hand rule, we define rotations anti-clockwise to have a positive angular velocity, while rotations clockwise are defined as negative angular velocity.

The angular acceleration (ɑ) is defined as the rate of change of angular velocity with respect to time, and can be calculated with

$$\alpha = \frac{\omega_{final} - \omega_{initial}}{t}$$

Or if plotted on an angular velocity-time curve, can be calculated as the first derivative of angular velocity, or second derivative of angular position.

$$\alpha = lim \frac{\delta\omega}{\delta t}\ as\ \delta t \to 0$$

Angular acceleration can be measured in degrees per second squared, however, once again if further calculations are required, it is best to use radians per second squared. Similarly, to angular velocity we can use the right hand rule to determine positive or negative angular acceleration with anti-clockwise being positive and clockwise being negative respectively.

1.4.4 Relationship between linear and angular motion

As we mentioned at the beginning of this chapter, many human movements can be considered linear movement, such as the movement of the body as a whole, from which we generally use the hip representing the bodies centre of mass; or, the endpoint of a segment. Motions about the individual segments that constitute the movement are angular, from which the motion of the segment end-point becomes linear. Therefore, there is a direct relationship between angular and linear motion which can be expressed mathematically. As mentioned earlier, to perform these calculations the units of measurement for angles must be in radians.

Given that we defined the radian as the angle from which the length of the circles arc is equal to its radius. The length of the arc travelled (s) can be calculated from the angle (θ) and the radius (r) by the equation

$$s = r\,\theta$$

And for instantaneous

$$\delta s = r\,\delta\theta$$

The linear velocity of a point on a rotating body is referred to as the tangential velocity (v_T), which acts as a tangent to the point on the curved path. It is calculated from the angular velocity (ω) and the distance from the centre (r), via the following equation

$$v_T = \omega\, r$$

And for instantaneous

$$\frac{\delta s}{\delta t} = \frac{\delta \theta}{\delta t}\, r$$

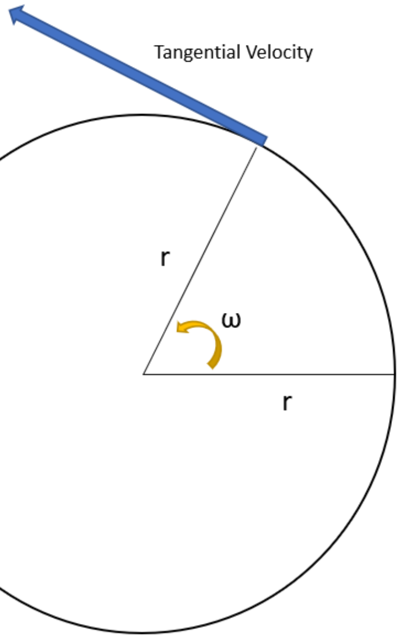


Figure 10: The linear velocity of a point of a rotating body

The linear acceleration of a point on a rotating body consists of two parts, the tangential acceleration (a_T) which acts as a tangent to the point on the curved path, and the centripetal acceleration (a_C) which acts toward the axis or centre of rotation. The tangential acceleration (a_T) is calculated from the angular acceleration (ɑ) and the radius (r) with the following equation

$$a_T = \alpha\, r$$

The centripetal acceleration, which acts toward the axis or centre of rotation, can be calculated from the angular velocity (ω) and the radius (r) with the following equation

$$a_C = \omega^2 r$$

Or alternatively with the tangential velocity (v_T) and the radius (r)

$$a_C = \frac{v_T^2}{r}$$

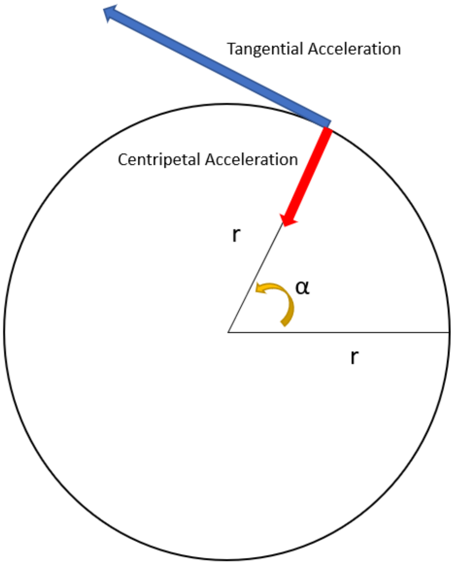


Figure 11: The linear acceleration of a point on a rotating body consists of two parts

1.4.5 Angle-Angle Diagrams

As we have seen, in human movement the combinations of angular motions about several joints can produce linear movement, with mathematical relationships. Further to this, due to us producing human movement by the rotation of body segments about one another, angle-angle diagrams can also produce insightful means of examining movement by looking at the relationship between two joints during movement. These diagrams are able to plot the angles of two adjacent body segments against the angle of another body segment. This also demonstrates the important benefit of kinematic measures that allow us to describe the characteristics of particular components of a skill/task during movement. These graphs generally contain a particular shape due to the sequence of the respective movement. The shapes of the curves can be analysed either pre or post injury, as well as in certain pathological populations providing valuable insights into potential movement defects.

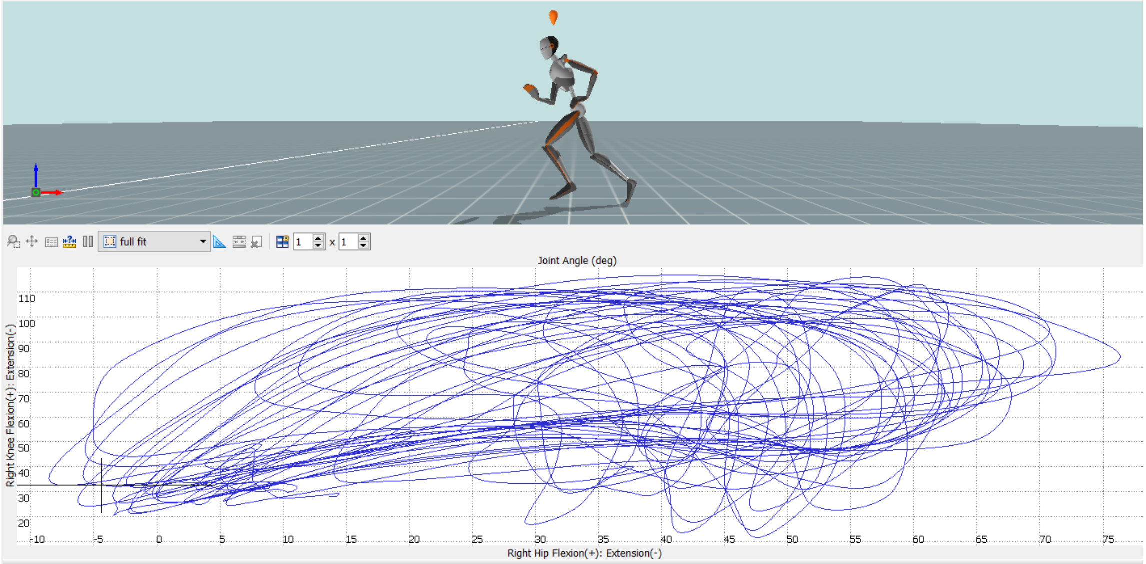


Figure 12: An example of an angle-angle diagram showing the shape of hip angles plotted against knee angles during running an Illinois agility course, shown from Xsens MVN[3]

1.4.6 Coordination of linear motion

With human movement requiring various segments of the body to interact, there are different approaches to coordinate the segments to achieve the desired end result. When the sequencing of segments is added simultaneously, we refer to this as an accuracy approach, or simultaneous movement. While, if the sequencing of segments follows a proximal to distal flow, we refer to this a maximum velocity approach, or sequential movement.

Accuracy approach

If a given performance requires a great deal of accuracy, such as shooting a free throw in basketball, or sinking a putt in golf, the sequencing of the segments is added simultaneously. The linear velocities of the respective segments reach their maximum levels at the same time, this enables a more controlled velocity of the endpoint than the maximum velocity approach. This brings about what we refer to as the velocity-accuracy trade-off, where some velocity is traded for accuracy.

Maximum velocity approach

If a given performance requires a high velocity at ball release or impact, such as throwing, kicking or hitting for distance; the sequencing of the segments follows a proximal (larger and slower body segments, such as the hips) to distal flow (smaller and faster body segments, such as the foot). Each segment adds to the velocity to the previous body segment when it has reached its maximum velocity, creating a staircase approach to the velocities. As a result, each segment endpoint reaches a maximum velocity followed by the next, enabling an optimal velocity of the most distal segment end point. This can be seen when athletes approach a kick for distance, you observe them approach the ball with a curved run up, the forward movement of the body creates a linear velocity of the hip, with the curved path enabling more hip rotation to increase this linear velocity. This then allows a greater contribution to the final velocity of the ankle.

1.5 Motor learning and coaching in movement analysis

1.5.1 Performance outcome vs performance production

It is essential for a practitioner or coach to develop the necessary expertise to analyse motor skills within a given domain, whether it be in a sport, clinical or workplace sense. This enables one to identify the part of the task that is deficient, allowing them to intervene appropriately. Further to this, if done consistently, it allows them to track improvements. There are several ways that success in this can be measured, in motor learning and coaching we refer to these as performance outcome measures and performance production measures[12].

Performance outcome measures
This is a category of motor skill performance measures that indicate the outcome or result of the skill. In a sports setting, consider someone coaching a basketball player performing a free throw, the performance outcome would be ensuring more successful goals in the net from a given number of free throws. In a clinical setting, consider a patient doing a timed up and go test, the performance outcome would be achieving a faster time in the test. Finally, in a workplace setting, consider an ergonomist optimizing a workstation in a factory, the performance outcome could be producing a higher number of items in the assembly process due to faster assembly times.

Performance production measures
This is a category of motor skill performance measures that indicates the performance of specific components of the motor control system while performing the action. In the above examples, the performance production measure of a basketball player performing free throws could be the amount of wrist flexion that occurs to put back spin on the ball. For the patient performing a timed up and go test, the performance production measure could be the stride length or stride rate during the gait component of the task. While for the worker in a factory assembly line, the performance production measure could be the amount of trunk lean to reach for individual components to assemble a product.

1.5.2 Providing feedback and coaching

We observed earlier in the biomechanical approach to motion analysis section, our motion analysis model which consisted of preparation, observation, evaluation, intervention and re-observation. We use this model to identify errors and provide feedback. It is important for the coach or practitioner to also understand how to provide this feedback, error information directs the person to change incorrect aspects of their performance, while feedback concerning correct performance encourages the person to continue performing in that manner. In addition to this, it is important for the coach or practitioner to also understand, what may be ideal for one person may differ to someone of a different age, gender or skill level.

1.5.3 Augmented feedback

Feedback that provides assistance to learning a motor skill can be intrinsic to the task itself, or it can be augmented feedback from an external source. In many cases intrinsic feedback may be sufficient for the learner to acquire a skill by making appropriate adjustments to their movements based on their own sensory feedback, or by watching the performance of others. However, it should be noted while learning new skills, individuals may not perceive the meaning of their own task-intrinsic feedback and in these cases may benefit from augmented feedback[12].

1.6 Kinetics

1.6.1 Introduction

Within Physics and Engineering disciplines, kinetics is the branch of mechanics that deals with the causes of motion, more specifically forces and torques. We saw in earlier chapters, kinematics was the study of describing motion, this will now be extended to kinetics, in which we explain why the motion is caused. Together, kinematics and kinetics form the dynamics of a body or system. If a motion is translatory, we use linear kinetics to understand the motion, using the concept of force. A linear force is any interaction that if unopposed, will change the motion of an object. If motion is rotary, we use angular kinetics to understand the motion, using the concept of torque. A torque, is the rotational equivalent of a linear force, which causes a rotation of an object. In order to understand the underlying nature of motion, one must understand the link between its cause and effect. This is explained with Newtons laws of motion.

1.6.2 Newtons laws of motion

Newtons three laws of motion demonstrate how forces create movement and form the basis of most human movement analyses in Biomechanics. They can be described with respect to both linear and angular motion:

Newtons first law

Newtons first law states that "*an object will remain at rest, or a state of uniform motion in a straight line, unless it is compelled to change that state, by a force*". This can be demonstrated when we are driving along in our car, if we take a sharp left turn, we seem to feel ourselves being moved to the right. This is because our body is still travelling in the original direction of motion, it is the chair and seat belt that apply a force on us to change direction. The inertia of an object is used to describe its resistance to motion and is directly proportional to the mass of an object. The greater the mass of an object, the greater its inertia and the harder it is to change its motion.

The angular motion equivalent can be described as "*a rotating body will continue in a state of angular motion unless acted on by an external torque*". As we described with linear motion, the measure of an object's inertia is its mass. The angular counterpart of mass, is called the moment of inertia, a quantity which indicates the resistance of an object to change angular motion. However, the moment of inertia is dependant not only of an objects mass, but the distribution of mass with respect to the axis of rotation. This can be demonstrated in a ski-jumper comparing a spin to a flip. While performing a spin, the bodies mass is distributed very close to the axis of rotation, whereas while performing a flip, the same mass is distributed further from the axis of rotation. This also explains why gymnasts and divers assume a tuck position while somersaulting, it brings the body mass closer to the axis of rotation, decreasing the moment of inertia and therefore decreasing the resistance to rotation.

Figure 13: The moments of inertia about different axes of rotation

Newtons second law
Newtons second law states that *"the change in motion of an object is directly proportional to the force applied on it and in the direction of the straight line in which it is applied"*. Newtons second law can be expressed mathematically relating force (F), mass (m) and acceleration (a) by the equation

$$F = ma$$

We can also see from this equation that, for larger masses a larger force is needed to create the same acceleration. When the force produces acceleration, the accelerating object will travel in a straight line along the line of action of the force. Forces are measured in units of Newtons.

The angular motion equivalent of this can be described as *"a torque will create an angular acceleration of a body that is directly proportional to and in the same direction of the torque, and inversely proportional to the moment of inertia of the body"*. This can also be expressed mathematically relating torque (τ), moment of inertia (I) and angular acceleration (ɑ) by the equation

$$T = I\alpha$$

We can see from this equation, that greater torques create greater angular accelerations, and that for a given torque, the angular acceleration is inversely proportional to the moment of inertia. This means that objects that have mass distributed further away from the axis of rotation will undergo smaller angular accelerations for a given torque. This can be demonstrated if you try to lift a weight held in your hand away from the body at the shoulder. If you keep the weight closer to your body with a bent arm, it is much easier than holding it further away from the body with an outstretched arm, to give it angular acceleration. Torques are measured in units of Newton-metres.

Newtons third law
Newtons third law states that *"every action has an equal and opposite reaction"*. According to Newton, whenever objects interact, they exert forces on one another, these forces always come in pairs and are called action and reaction forces. The size of these forces are always equivalent and are in opposite directions from one another. Consider someone rowing a boat, the rower uses the oars to push the water backwards, since

forces result from mutual interactions, the water must also be pushing on the oars, propelling the boat through the water. The size of the force on the water equals the size of the force on the oars, the backward direction of the force on the water, is in the opposite direction of the forward force on the oars. Action reaction force pairs make this movement of the boat through the water possible.

The angular motion equivalent can be described as *"for every torque applied by one body on another body, there is an equal and opposite torque applied by the second body on the first body"*. Generally, the torque generated by a given body segment, creates a counter-torque by another body segment. An example is rotating the lower legs during jumping, to counteract the lower body torque, the upper body will rotate in the opposite direction, creating a torque equal and opposite to the lower body torque.

1.6.3 Linear kinetics and forces

Linear kinetics is used to understand translational motion, using the concept of force. A force is any interaction that if unopposed, will change the motion of an object. Forces are a vector quantity, having both magnitude and direction with the ability to produce motion, stop motion or change direction. Therefore, a force is any interaction between any two or more objects, that can either push or pull, causing them to accelerate positively or negatively. There are two characteristics of a force that one must consider, these are the line of action of the force and the point of application. The line of action of a force is a straight line of infinite length along the direction that the force is acting. The point of application is the specific point at which the force is applied to an object, importantly, the point of application of a force can determine if the resulting motion is linear motion, angular motion, or a combination of both.

Gravitational forces and weight
These are the forces that keep us grounded. This can also be used to explain the difference between an objects mass and its weight. Its mass is essentially how much matter it contains and is measured in kilograms, whereas an objects weight is a downward force caused by the acceleration due to gravity. We remember from Newtons second law that a force was equal to the product of mass and acceleration, therefore an object's weight is its mass multiplied by the acceleration due to gravity, expressed mathematically as

$$Wt = mg$$

The acceleration of gravity on earth is equal to 9.81ms^{-2}. If you were to think about an astronaut on the moon jumping around, they have the same mass as on earth, but with a much lower acceleration due to gravity, their weight is much smaller. Given that weight is a force, it is a vector having not just magnitude but direction. The line of action of this force is straight down (toward the centre of the earth), and its point of application acts on the centre of mass.

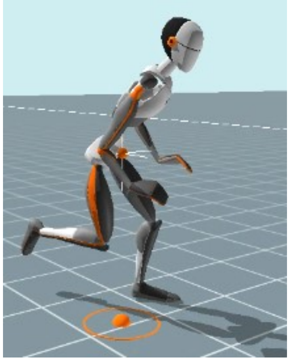


Figure 14: The centre of mass shown as the orange sphere during an agility run, in Xsens MVN[3]

Ground reaction force
If we remember from Newtons third law, every action has an equal and opposite reaction. When we stand on the ground, our weight which is equal to our body mass times gravity pushes down on the ground. The ground reaction force (GRF) pushes back at an equal magnitude and opposite direction. When walking this GRF can be 1.2 times the body weight, during running it is around 3 BW's, and during jumping can be up to 7-9 BW's. The ground reaction force, being a vector can be resolved into its x, y and z components and acts through the centre of pressure (COP). The GRF is typically measured using a force platform and is presented as a vertical component (up and down), anteroposterior component (forward and backward) and mediolateral (side to side).

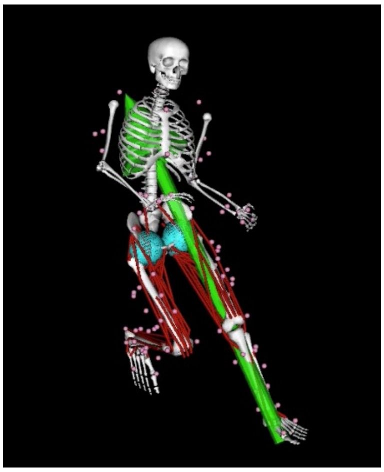


Figure 15: The ground reaction force shown in green during a sidestep shown in Opensim[10], using data from Konrath et al. (2017)[13]

Muscle force
When skeletal muscles of the body contract, they move the bones of the skeletal system. Furthermore, these contractions can facilitate maintenance of posture and stability of joints. The origin and insertion points of a muscle describe the attachment points of the muscle on the bone, with the insertion point typically moving toward the origin point when the muscle contracts. A muscle force is not possible to measure due to its invasiveness, however, they can be estimated using musculoskeletal modelling approaches. Each muscle can be assumed to act as a single force vector, with its direction moving through the line of action of the muscle and acting through the muscle attachment point, this force vector can be resolved into its components. In a two-dimensional sense, one component will cause rotation at the joint while the other component acts toward the joint centre.

Joint reaction force
The joint reaction force is the net force acting across the joint, and exists as equal and opposite forces between adjacent bones. It is caused by the weight and inertial forces of two segments. Generally, the magnitude of this force is unknown and must be calculated via the process of inverse dynamics. Briefly, given the appropriate kinetic and kinematic data, combined with anthropometric information such as the body dimensions and moments of inertia of segments; Newtons second law can be used to calculate the net force acting at the proximal end of a segment, provided the force is known at the terminal end of the segment.

Joint contact force

It should be noted that the joint reaction force is not the same as the joint contact force, or the bone on bone force across a joint. The joint contact force also comprises the contributions of contracting muscles pulling the joint together. If you think about it, muscles cross a given joint to be able to create movement between the connecting segments, when the muscle contracts, it pulls the bones together, increasing the contact force. Given that muscle forces are needed to calculate this, musculoskeletal modelling approaches must be used to estimate the joint contact force.

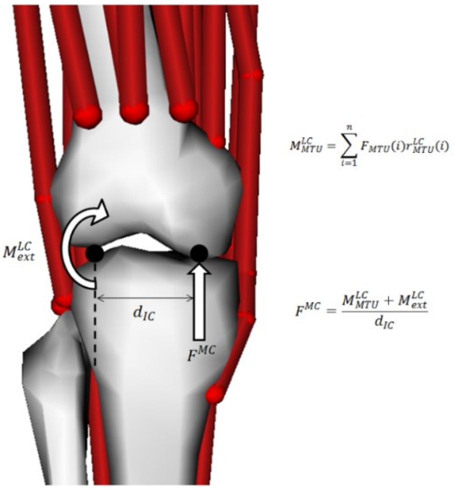


Figure 16: A knee joint contact model, using muscle forces and joint torques to estimate medial and lateral compartment contact forces, Image from Konrath et al. (2016)[9]

1.6.4 Angular kinetics and torques

Angular kinetics is used to understand rotational motion, using the concept of torque. When a force causes a rotation, the rotation will occur about a fulcrum or a pivot point. The line of action of the force will be at a certain distance away from the pivot point, the shortest or perpendicular distance to the pivot point is known as the moment arm. The torque (τ) is defined as the product of the force (F) and the moment arm (r), expressed mathematically as

$$\tau = Fr$$

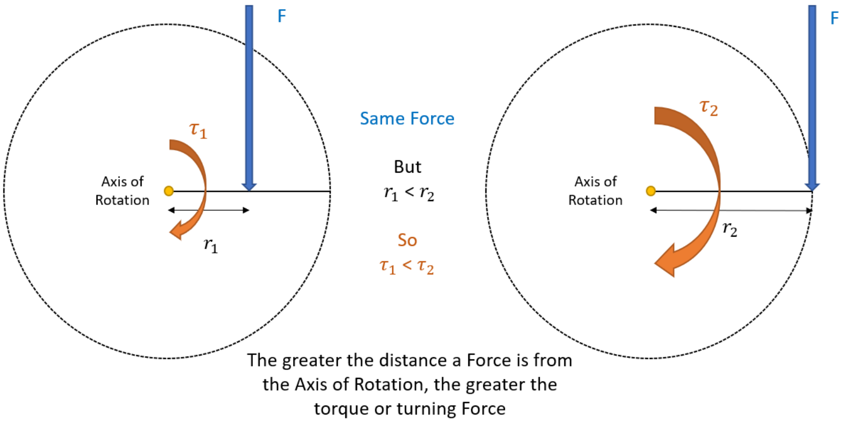


Figure 17: The effect of moment arm of a force influences the torque

A torque is a force that has a tendency to cause rotation about a specific axis and is measured units of Newton-metres. If the force were to act directly through the pivot point or axis of rotation, the torque would be zero, due to the fact that it does not have a moment arm. You will also see the term moment instead of torque throughout the literature, the terms are used interchangeably and refer to the same thing.

Moment of inertia

As discussed in Newtons laws, the moment of inertia is a quantity which indicates the resistance of an object to change angular motion. The moment of inertia is dependant not only of an objects mass, but the distribution of mass with respect to the axis of rotation. For the rotation of a body segment, the critical factor in how it rotates, is how the mass is distributed about the point that the segment is rotated about. We calculate the moment of inertia using the following equation

$$I = \sum mr^2$$

Where (I) is the moment of inertia, Σ means the sum of, (m) is the mass, and (r) is the distance of the mass to the axis of rotation. The moment of inertia applies to the body in sporting movements. Consider an Olympic diver that assumes a tuck position while somersaulting, it brings the body mass closer to the axis of rotation (so the value (r) in the above equation is smaller), decreasing the moment of inertia and therefore making it easier to rotate.

Figure 18: An Olympic diver assuming a tuck position to decrease their moment of inertia

Individual body segments have their own inertial properties based on the mass of the respective segment, and where the centre of mass is located. These can be measured with methods including cadaveric analysis, DEXA or underwater weighing. Regression equations also exist that allow one to estimate the mass of segments with respect to the total body mass, as well as where the centre of mass lies within the segment with respect to the segment dimensions.

1.6.5 Linear and angular momentum

Linear momentum

Linear momentum (p) is a quantity relying on both mass and velocity, it is defined as the product of mass (m) and velocity (v), and expressed mathematically as

$$P = mv$$

A heavy football or rugby athlete running slow may have the same momentum as a lighter player sprinting at full speed. Momentum is a very important quantity, as it relates very closely with force. In fact, the product of force and time (how long a force is applied for) creates what we call impulse and is responsible for creating, changing, or stopping momentum. This relationship is explained below

Remember from Newtons second law that force equals mass times acceleration

$$F = ma$$

And we also know that acceleration is the change in velocity with respect to time

$$a = \frac{\Delta v}{t}$$

Which means that force can also be expressed as the change in momentum with respect to time

$$F = ma \qquad \text{becomes} \qquad F = m\frac{\Delta v}{t}$$

And from this we see that Impulse is equal to the change in momentum

$$Ft = m\Delta v$$

Impulse is an important concept that applies to both force production and force absorption. Consider rowing a boat along the river, a rower pulls the oar towards the water and due to Newtons third law, the water pushes back on the oar propelling the boat forward. For a given stroke, if the rower just applies a force for a short time producing a small impulse, the boat won't change much momentum. Whereas, if they apply the force for a longer period of time, a greater impulse is achieved and the boat gains more momentum. Impulse also applies to force absorption, which is why runners wear shoes that cushion forces at impact, it helps to reduce the effects of large ground reaction forces.

When collisions occur between two bodies, the total momentum of the system remains unchanged according to the law of the conservation of momentum. That is the total momentum before a collision is equal to the total momentum after a collision. However, in reality some energy is lost during collision as sound or heat. These concepts of momentum conservation become important when analysing collisions in sports such as tackling in rugby, hitting a ball in baseball, or teeing off in a game of golf.

Angular momentum

Angular momentum (H) is the angular equivalent of linear momentum and is therefore the product of the moment of inertia of the body (I) and its angular velocity (ω), expressed mathematically as

$$H = I\omega$$

Similar to linear motion, where a force is equal to the time rate of change of linear momentum; a torque is equal to the time rate of change of angular momentum. This is a direct consequence of Newtons second law, in order to change angular momentum a torque must be applied. This also means that without an external torque, angular momentum cannot change. This becomes important during activities that contain aerial movements, such as jumping or flight. Once take-off has occurred and the body is no longer in contact with the ground, angular momentum can no longer change, because gravity acts through the centre of mass and will not create rotation. When in the air, angular momentum remains constant according to the conservation of angular momentum. All angular momentum must be generated prior to leaving the ground, which is why you will see a gymnast perform a run up prior to take off in order to generate as much angular momentum as possible.

Figure 19: A gymnast acquiring as much momentum as possible prior to leaving the ground

Once they have left the ground, the angular momentum will not change. However, they can manipulate their body to spin faster or slower, due to the inverse relationship between their moment of inertia and their angular velocity (Angular momentum equals moment of inertia multiplied by angular velocity). The larger the moment of inertia, the smaller the angular velocity and vice-versa.

Consider the Olympic diver we described earlier, they initially leave the spring board with a straight body, meaning they will spin slowly; once they form a tuck position, they rotate must faster as the moment of inertia becomes lower (the mass is closer to the axis of rotation), then prior to entering the water they straighten up again increasing the moment of inertia and decreasing the angular velocity. Throughout the entire flight phase angular momentum was conserved, however they influenced their rotation speed with their body positioning.

1.6.6 Modifying lever lengths in sport

We have seen that skeletal muscle initiates the movement of adjacent bones connected at a joint. This is an example of a lever in which the muscle creates a torque to create angular motion of the bones about the joint, which is the axis of rotation. The distance from the axis of rotation (the joint) and the muscle force (applied at the muscle attachment point, and aligned with the muscles line of action), is called the *force arm.* While the distance between the axis of rotation (the joint) and the load/weight/resistance (such as a weight held in the hand), is called the *resistance arm*. The most common type of lever in the body is the 3rd class lever, in which the force, is somewhere between the axis of rotation (the joint) and the load/weight/resistance. Third class levers are not mechanically efficient, the force arm will always be smaller than the resistance arm. However small movements of the attachment point, creates larger movements further down the bone, this allows a larger range of motion of the bone, without large changes in muscle length.

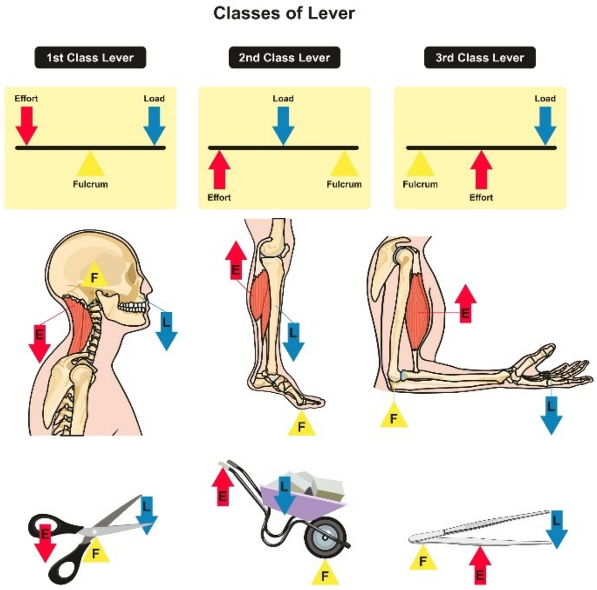


Figure 20: The various types of levers of the human body

For force related activities, we aim to reduce the length of the resistance arm by flexing at the joint to improve the effectiveness of the force arm, such as in weightlifting. This overcomes the deficiency between the force arm and the resistance arm.
When velocity of movement is required, such as a tennis serve, or in throwing applications, we aim to increase the length of the resistance arm by extending at the joint, prior to impact or release. If we remember from angular kinematics, tangential velocity increases as we move further from an axis of rotation at a given angular velocity.

While throwing or pitching, the elbow is initially flexed at the beginning of the throw, lowering the resistance arm which lowers the moment of inertia and allows a faster angular velocity to developed. Prior to ball release, the elbow is then extended increasing the length of the resistance arm, and increasing the velocity of the segment endpoint. This achieves a higher velocity throw.

Figure 21: How we control lever arms to achieve a high velocity throw

1.6.7 Forward and Inverse dynamics

We have observed that mechanical analysis can focus on forces and torques (kinetics), or on the motion parameters without forces (kinematics). We have further observed direct cause and effect relationships between kinematics and kinetics with Newtons laws. When it comes to human movement, we can adopt several approaches with this relationship. One is through forward or direct dynamics, and the other is through what we call inverse dynamics.

Forward dynamics is the process of calculating kinematic information (positions, velocities and accelerations) from measured kinetic information (joint forces and joint torques). Simply put, forces cause movement. Forward dynamics is deterministic meaning there is only one solution. Inverse dynamics on the other hand, is the process of calculating kinetic information from measured kinematic information. Simply put, the motion was caused by forces. However, inverse dynamics is not deterministic, with an infinite number of solutions, as there could be any infinite number of forces acting on the system.

Inverse dynamics is a specialised branch of mechanics, in which forces and torques are indirectly determined from the kinematics and inertial properties of moving bodies. It is a derivation of Newtons second law, where resultant force is partitioned into known and unknown forces. All of the unknown forces are combined to form a single net force across the joint to be solved. Similarly, all of the unknown torques are combined, so that a single net torque can be calculated. In Biomechanics this becomes useful, because it allows us to calculate net joint torques, and therefore determine which muscle groups may be active and whether they are working concentrically or eccentrically (ie. Whether a muscle group is generating power, or absorbing power).

Now if we remember from Newtons second law, if we sum all of the external forces acting on a segment, the resultant force (F) is proportional to the segment's acceleration (a). Further, if we sum all of the torques acting on a segment, the resultant torque (τ) is proportional to the segment's angular acceleration (α) about a particular axis. Based on these laws, inverse dynamics is able to be performed, if we know the segment's mass and moment of inertia

$$\sum F = ma \qquad \text{and} \qquad \sum \tau = I\alpha$$

So, knowing these relationships, we split up the body into segments within a kinematic chain and assume each segment is a rigid body, from which we can create free body diagrams. It should be noted that some form of force measurement is needed at the most distal segment, otherwise inverse dynamics cannot be performed. Using the lower limb as an example, ground reaction forces could provide this force information, which could be measured from a force plate or force shoe. Recent algorithms also exist to estimate the ground reaction force[14–16], however this will not be as accurate as force measurement.

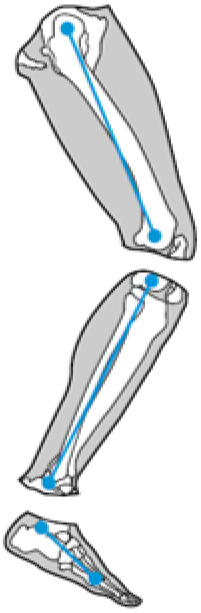


Figure 22: Splitting up the body into segments of a kinematic chain

Once we know the force applied at the most distal segment of the kinematic chain, we use an ordered approach starting with the most distal segment. We develop a free body diagram of the segment showing the ground reaction force, the weight of the segment, and a single unknown joint reaction force and joint torque acting on the other end of the segment.

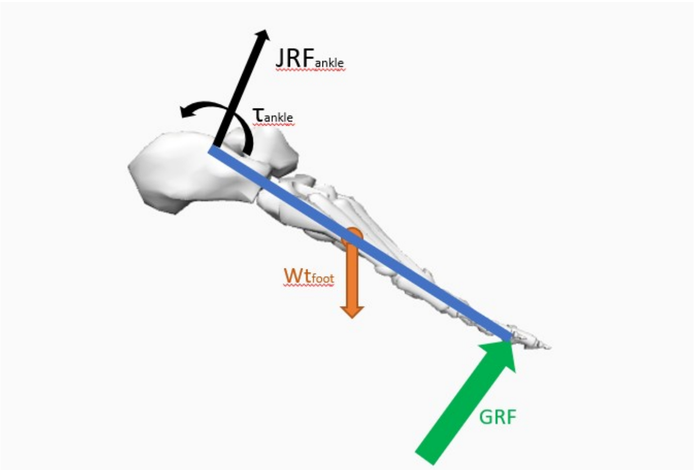


Figure 23: A free body diagram of the foot to determine a single joint reaction force & torque

Given that we have measured the acceleration and angular acceleration of the segment, we can use the kinematics, along with the measured force and mass and inertial properties, to solve for the unknown single net force and torque using Newtons equations. Once we have solved this force and torque, this represents the joint reaction force and torque. Moreover, this gives us the known force and torque for the next segment in the kinematic chain. And we simply work our way up the chain to solve the net forces and torques at each joint.

It is important that we understand the net forces and torques at the joint that we have computed, are the representation of all of the structures crossing the joint. These structures include muscles, ligaments, the joint capsule and bone-on-bone forces, however to use each of these structures within a free body diagram, would create more unknowns than equations, making it in indeterminate and unable to be solved. This is why we just represent all of them as a single force and torque, to make the system determinate. That's not to say, they cannot be estimated. The field of neuromuscular biomechanics is dedicated to estimating these forces including muscle forces, ligament forces and joint contact forces using very advanced neuromusculoskeletal models.

2 Practical Lessons

2.1 Fundamentals of Inertial Measurement Units

Purpose
The aim of the following laboratory is to gain an understanding of the components within an inertial measurement unit

Task
In the following lab we will be tasked with investigating how an IMU collects data, and how different motions produce signals

Background reading
For background theory refer to the section on kinematics and inertial measurement units of the theoretical framework.

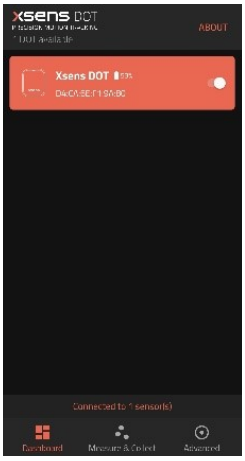
Equipment

- 1 Xsens DOT sensor
- Mobile phone or iPad
- Xsens DOT application

2.1.1 Part 1: Connect the sensors

- Plug in the USB cable to a power source to turn on the sensors. Place the sensor on a table away from any sources of metal. This is to ensure a homogenous magnetic field environment. Make note of the sensor coordinate system to know which direction the axes are running.

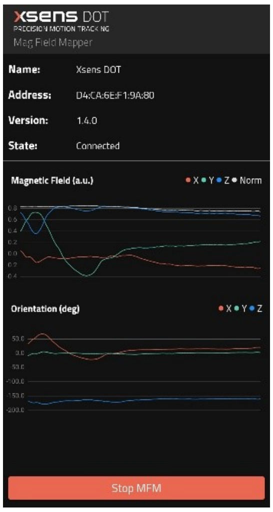
- Open the Xsens DOT application from either your mobile phone or Ipad, and ensure the blue tooth function is enabled.
- You will see the detected sensors on the dashboard, it will present the device ID, the battery status, as well as the option to enable the sensor with a button, slide the button across to enable the sensor, it will appear red.



2.1.2 Part 2: Mapping the magnetic field

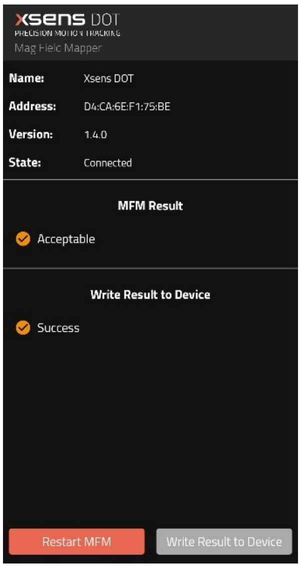
As we discussed in our chapter on inertial measurement units, the direction of the earth's magnetic field is used to determine the heading of the sensor and used as a reference in the calculation of 3D orientation. Ferromagnetic objects in close proximity within the environment may cause distortions to the magnetic field. It is recommended that we carry out the magnetic field mapper to calibrate the magnetometer to the local magnetic field.

- Click on the Advanced tab of the App, and select the Magnetic Field Mapper option, you will then have the option to choose which sensor to map, you can then start magnetic field mapping. Perform slow rotations about each of the respective axes x, y and z. You will see the magnetic field about each axis of rotation along with a white line presented as norm. Below the orientation of the sensor is plotted as Euler angles. When you have completed rotations about each axis, you can stop.



Name: Xsens DOT
Address: D4:CA:6E:F1:9A:80
Version: 1.4.0
State: Connected

- When you have completed the rotations, stop mapping and allow the data to be processed. The application will let you know if the result was acceptable or poor, with the option to write the result to the device.



Name: Xsens DOT
Address: D4:CA:6E:F1:75:BE
Version: 1.4.0
State: Connected

MFM Result

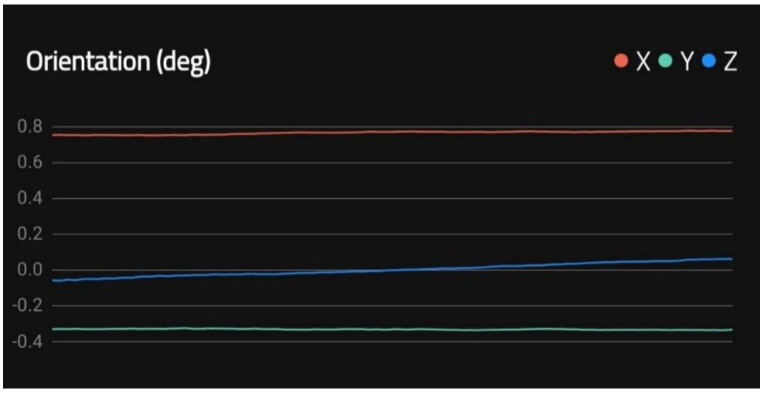
✓ Acceptable

Write Result to Device

✓ Success

2.1.3 Part 3: Orientation of the sensor, Roll, Pitch and Yaw

- Now we can begin to see how the sensors work. Select the option to collect data in real-time, and select the setting which allows you to collect orientation, angular velocity and free acceleration. The first thing we will look at is the orientation, place your sensor on the table pointing in a Northerly direction, you can double check with a compass if desired. You will notice the orientations are at zero, this is because the sensor is aligned North.

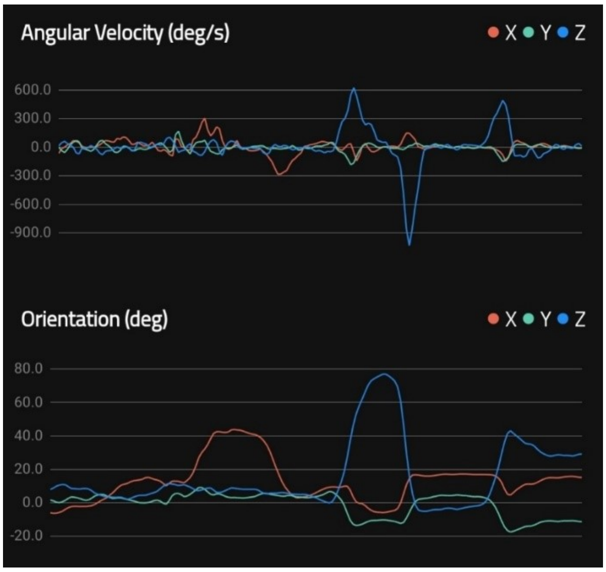


- Next remembering the axis directions from the sensor coordinate system, we will investigate how the orientations change about each axis, when we rotate the sensor. Let's start with Z axis, if we remember the right-hand rule, if we have our right hand with curled fingers and thumbs up pointing in the positive direction of the axis, then the curled fingers indicate the positive rotation direction, which is anticlockwise. Rotate the sensor anticlockwise and make note of how the orientation changes about the Z axis, it will increase. When you move past 180 degrees, you will see the sign flip, and start to move towards zero. Likewise starting at zero and rotating clockwise, you will see the opposite. The value of the orientation about the Z axis is known as **Yaw angle**.
- Repeat the same process for the X axis, this is known as the **Roll angle.**

- Repeat for the Y axis, this is known as the **Pitch angle**.

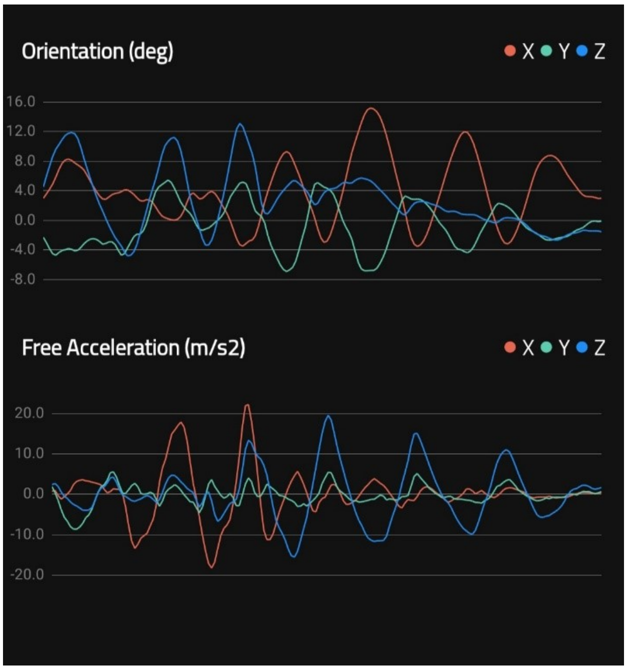
2.1.4 Part 4: Angular velocity

- Using the right-hand rule again, align your thumb with the positive direction of each axis, and note the direction of the curl of your fingers, this will indicate which rotation will indicate positive or negative angular velocity. Rotate the sensor slowly and also quickly in both anticlockwise directions and make note how the angular velocity changes.
- Repeat this for all axes X, Y and Z



2.1.5 Part 5: Free acceleration

- Now have a play around with the free acceleration. Rather than rotations, translate the sensor (move the sensor linearly along the different directions). Making note of which direction along each axis is positive and negative for the sensor coordinate system, begin moving the sensor both quickly and slowly in each direction and make note how the plots change.
- These values are known as the free acceleration, which means the acceleration due to gravity has been removed.



2.2 Setting up a Linked Segment Model and calculating a joint angle

Purpose
The aim of the following laboratory is to gain an understanding sensor to segment alignment, forming a linked segment model and calculating the angle between 2 segments.

Task
In the following lab we will be tasked with forming a linked segment model between the upper arm and lower arm, and calculating the angle between the two segments.

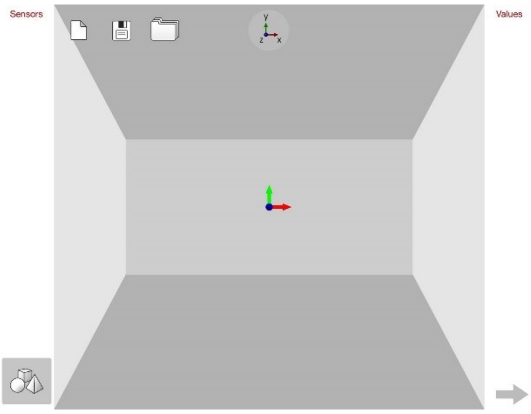
Background reading
For background theory refer to inertial measurement units of the theoretical framework. The graphical user interface of KineXYZ can also be read in the user manual, and also if any functionalities of the software need further clarification.

Equipment

- 2 Xsens DOT sensors
- iPad
- Xsens DOT KineXYZ application

2.2.1 Part 1: Get familiar with the GUI

- ➢ Begin with just a quick acquaintance of the GUI, more detailed instructions can be found in the KineXYZ user-manual, but briefly



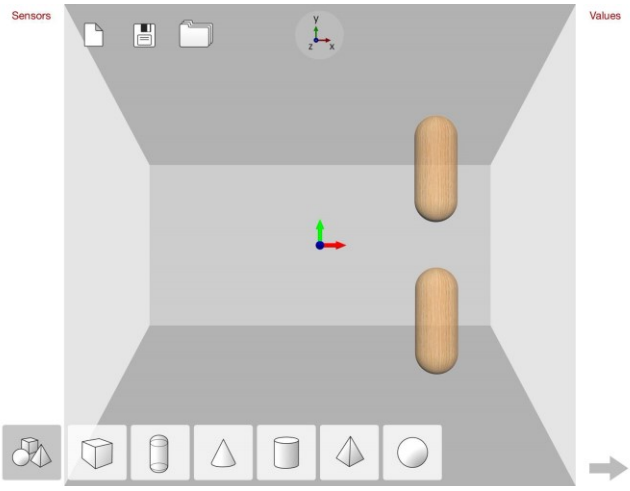
- ➢ The Sensors column on the left can be dragged to the right, to scan for DOT sensors, and will appear in this column.
- ➢ On the bottom left of the GUI, you will see the Shapes button, which you can select objects of various shapes and geometries.
- ➢ Top left of the screen, you can see New screen, save and open tabs.
- ➢ In the centre you see the Global Origin, and the Global coordinate system definition for KineXYZ. In this given coordinate system, the X axis moves horizontally, with positive pointing right; the Y axis moves vertically, with positive pointing up; The Z axis moves in and out of screen, with positive pointing out of the screen. You can also rotate around the space and see things from different planes and you will see the axes change accordingly. You can click the axis on the

top to go back to the default viewing. You can also zoom in or out by moving two fingers on the screen further apart or together respectively.

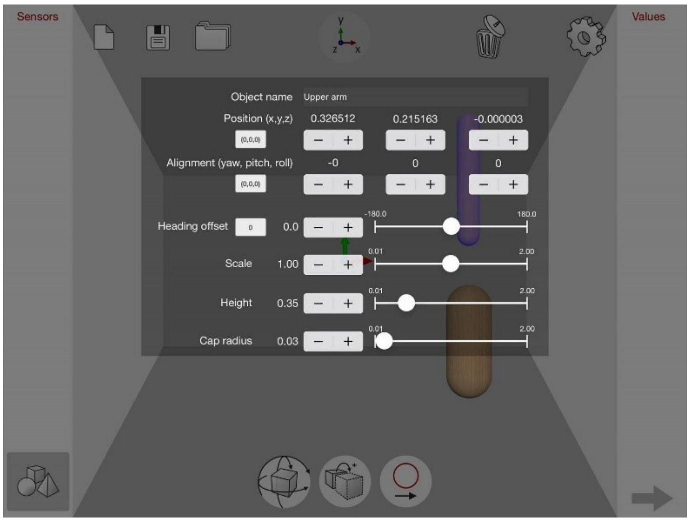
- On the right column, you will see an arrow at the bottom, this takes you into the function diagram section, which we will come back to later. Later when we have objects that we wish to use their positions or orientations to build functions with will appear in this column under values.

2.2.2 Part 2: Build the Linked segment model

- Pressing the shapes button in the bottom left corner, you will see the selection of objects to choose from, choose the capsule second from the left and drag two of them into the viewer.



- Select the top capsule and you will see it become highlighted blue, when something is highlighted you have the option to delete with the bin icon that appears in the top right corner, or to go into the settings mode. Select the settings icon.



Object name: Upper arm

Position (x,y,z): 0.326512 0.215163 -0.000003 (0,0,0)

Alignment (yaw, pitch, roll): -0 0 0 (0,0,0)

Heading offset: 0 0.0 (-180.0 to 180.0)

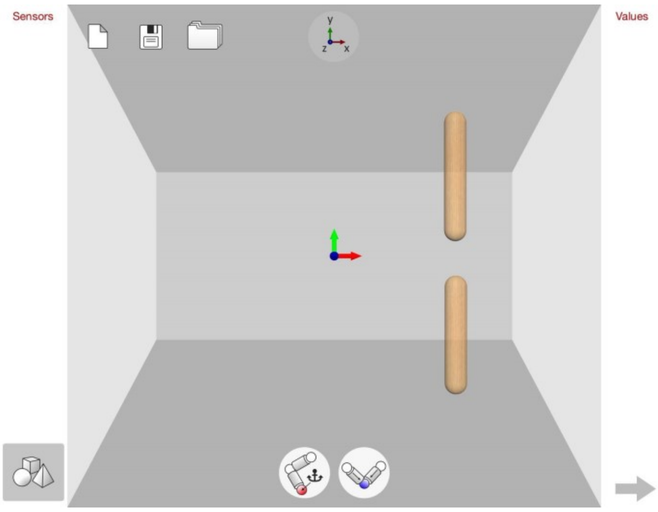
Scale: 1.00 (0.01 to 2.00)

Height: 0.35 (0.01 to 2.00)

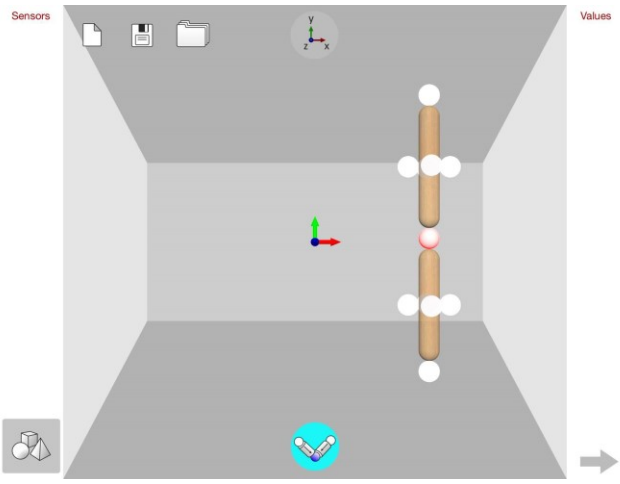
Cap radius: 0.03 (0.01 to 2.00)

- Within the settings, you'll see you can manually adjust its position, its alignment, the heading offset, and the geometries. Name the object 'Upper arm', change the cap radius to 0.03, and for now just estimate the length of the upper arm, to change in the height section. In one of the lessons building an upper body model, we will actually take some anatomical measurements.

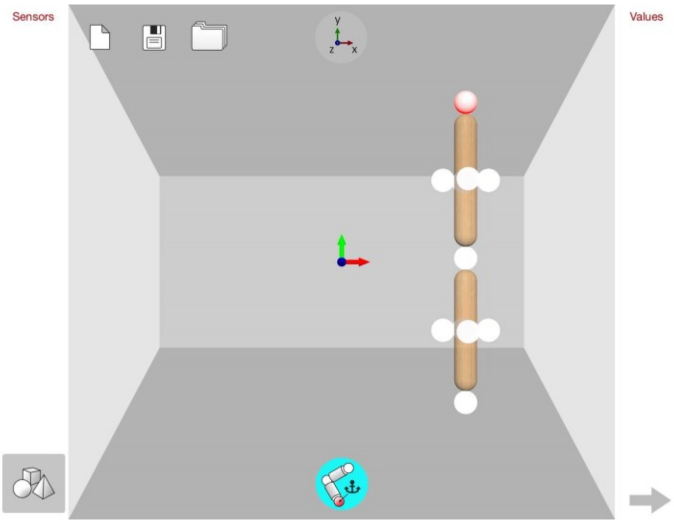
- Repeat the same for the bottom capsule and name it ‘Lower arm’. You will then see something like this below



- Next, we would like to fit the two objects together in a joint, once objects are in the viewport, there are two buttons at the bottom, one with a red sphere and anchor, the other a blue circle. Press the button on the right with the blue sphere, which is the set joints, when this is pressed the objects will present white spheres which are joint attachment points, select the bottom of the Upper arm, and the top of the Lower arm. You will see a joint form between the two segments now.



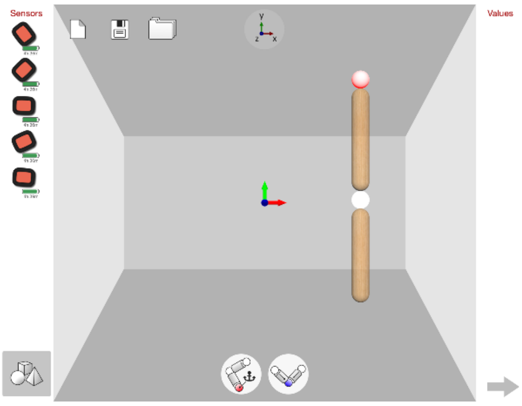
- Joints are coloured blue, and anchor points are coloured red, initially the middle joint will be coloured red as, you can see. However, we would like to set the most superior segment of the kinematic chain as the anchor. To do this, press the joint button again to click out of that selection mode. And this time, select the red sphere and anchor option, again you will see the white spheres present themselves, click the top of the upper arm to set the anchor there.



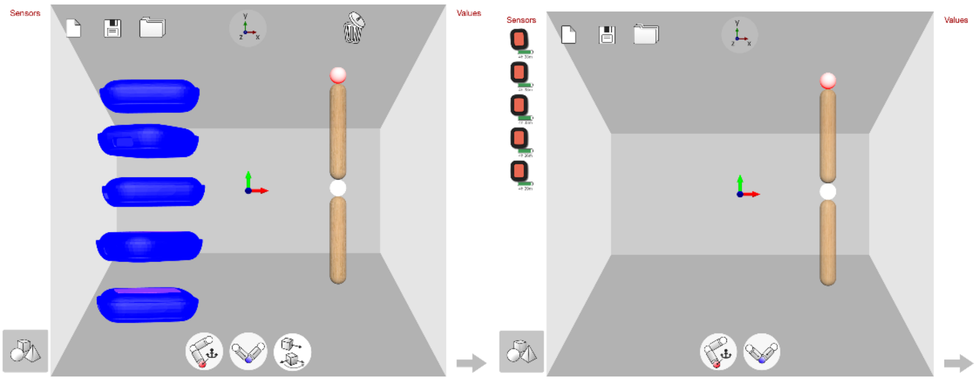
- You can now save this model by clicking the save button, save your model with your name and call it Upper arm model.

2.2.3 Part 3: Assign sensors to the segments

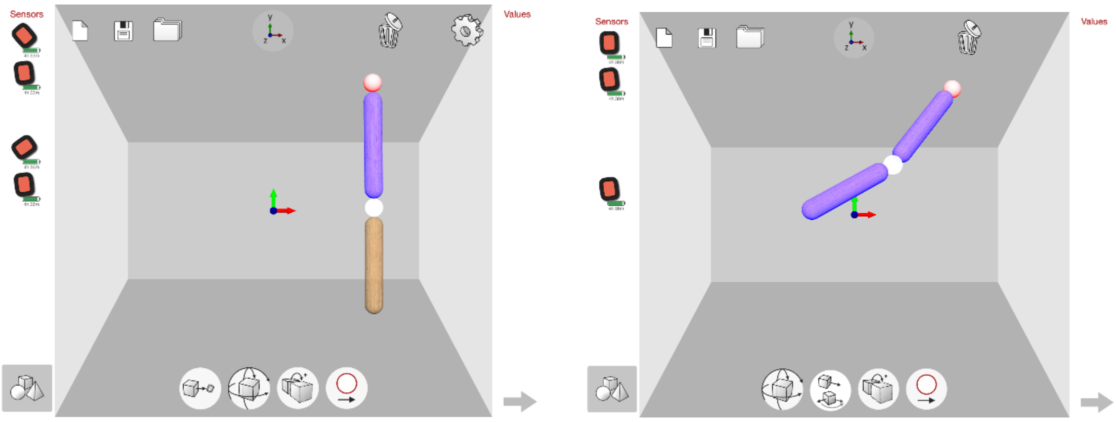
- Switch on your sensors by plugging them into a power source with the USB cable.
- Next, drag the sensors column in the GUI to the right, to put the Application into detect mode, the detected sensors will then appear in the sensor's column, once they are all in there, drag the column back to the left to get out of detect mode.



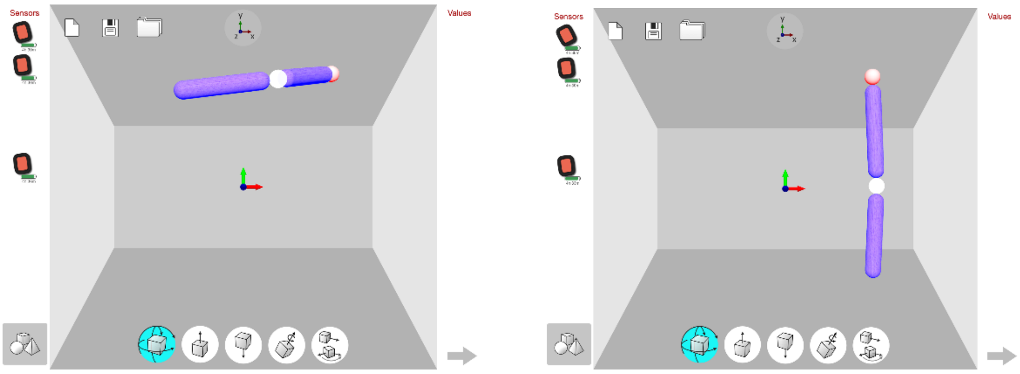
- It is important that we reset the orientations of the sensors, to do this, leave the sensors in the charging case and lie them flat on the table. Following this, bring the sensors from the Sensors column into the viewport, and select them all. You can then press the align sensors button on the right side (the cubes with arrows). After you do this they will all face the same direction. Before you can assign them to a segment, they need to be put back in the sensors column, to do this keep the sensors highlighted and press the trash can button, they will end up back in the Sensors column.



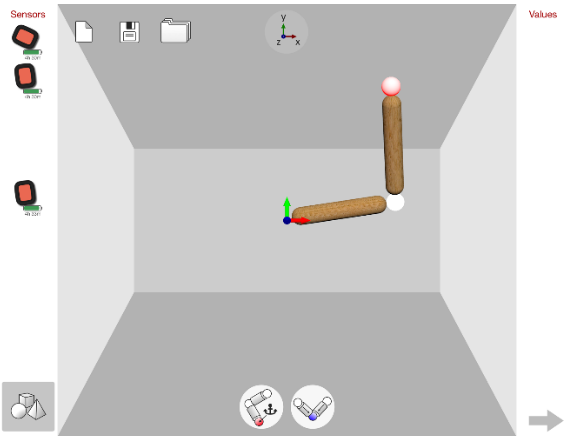
- You will then be able to assign any given sensor to a segment. Picking one sensor up you can rotate it and you will see it move in the sensor column so you know which one it is. This first one will be the upper arm, you can strap it to your arm and move that sensor onto the upper arm segment in the GUI. You will see the segment highlight blue when you have done this. Repeat the same process for the lower arm, identify the sensor, strap it to your forearm and drag from the column onto the segment.



- Once the segments have been assigned their sensors, select and highlight all segments and press the cube with rotation circles around it on the left, this is to do alignment. This is what we call sensor to segment calibration, we are putting your arm into a known position to calibrate the model to. Keeping your arm completely straight with no bend in the elbow and holding your arm by you side, keep your arm vertical. Then click the button with the cube and the arrow pointing up.

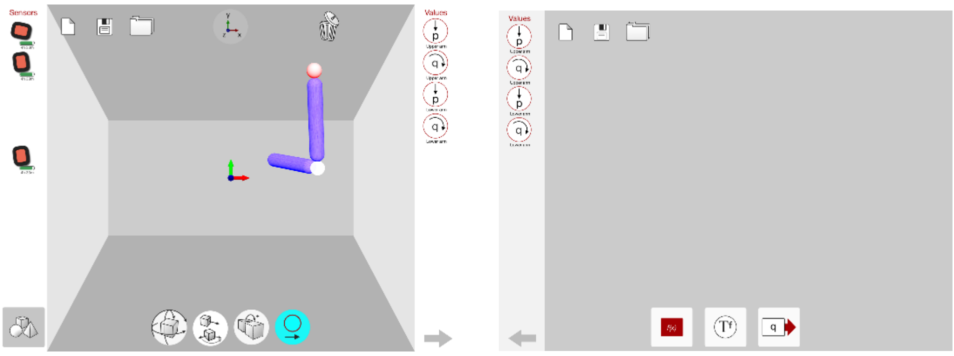


- The sensors will now be calibrated to your segments in the known position, and you will start to see your arm movements on in the GUI.

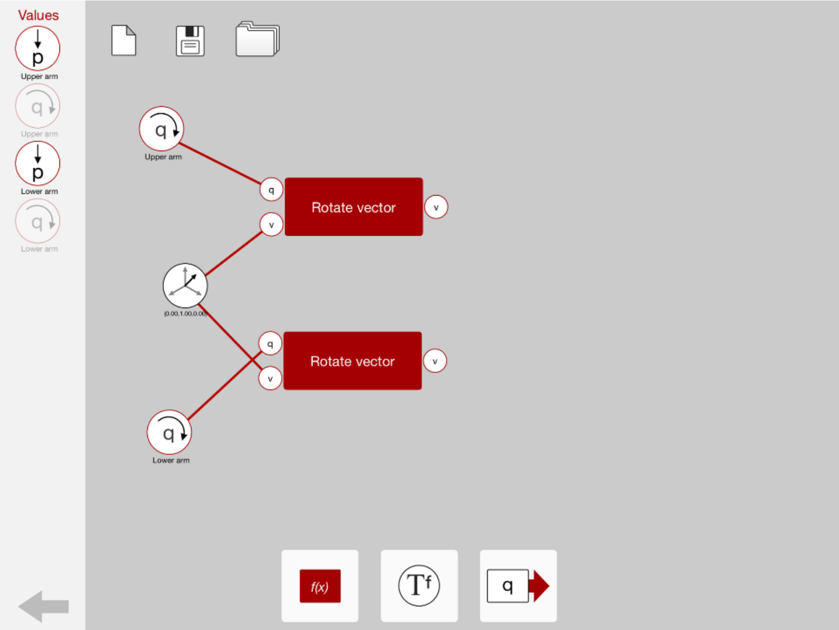


2.2.4 Part 4: Calculating a joint angle

- Now that everything has been calibrated each segment can have its position and orientation measured. Highlight all of the segments, and click the values button an the bottom, you will see position and orientation representations appear in the Values column on the right. If you press the arrow at the bottom right corner, it ill take into the dataflow section where you can create functions with the values you selected.



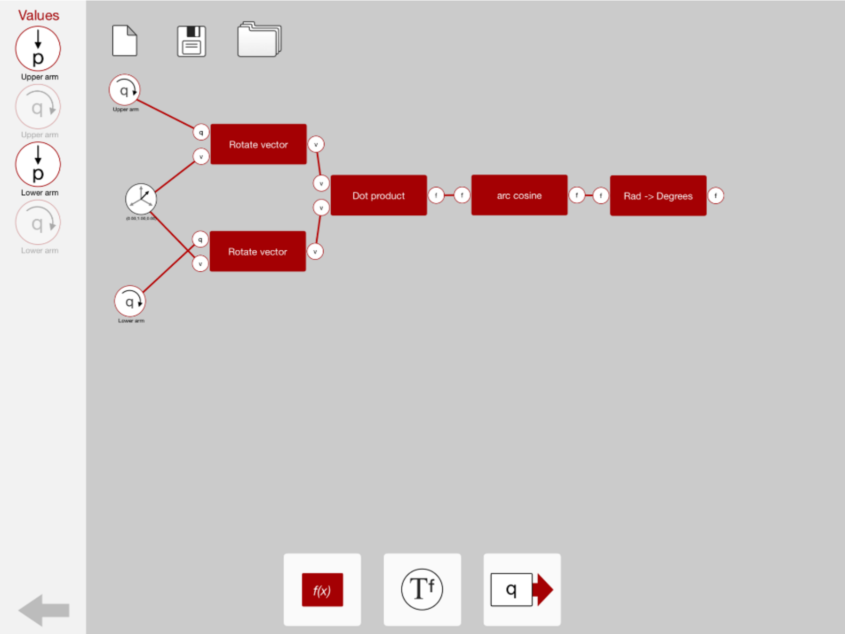
- Each of the segments were initially aligned to the y-axis. We can calculate the direction of a rotated y-axis of each corresponding segment. We will use these to calculate the angle between the longitudinal axes of the segments. We can do this with a function that takes a quaternion as an input, along with a unit vector representing the y axis <0,1,0>.
- Drag a red function box into the GUI, and select Rotate vector from the list. In addition to this, drag a constants circle in as well and select vector. Click the vector so that it is highlighted and go into its settings, you will need to set the x, y and z axis values, which you will put in 1 for the y axis.
- Drag into the GUI the quaternion for the Upper arm, if you then press it so that it is highlighted, and then click the q component of the rotate vector function, you will see a line form between the two. Now, if you press and highlight the v component of the rotate vector function and click the vector button, you will also see a line form.



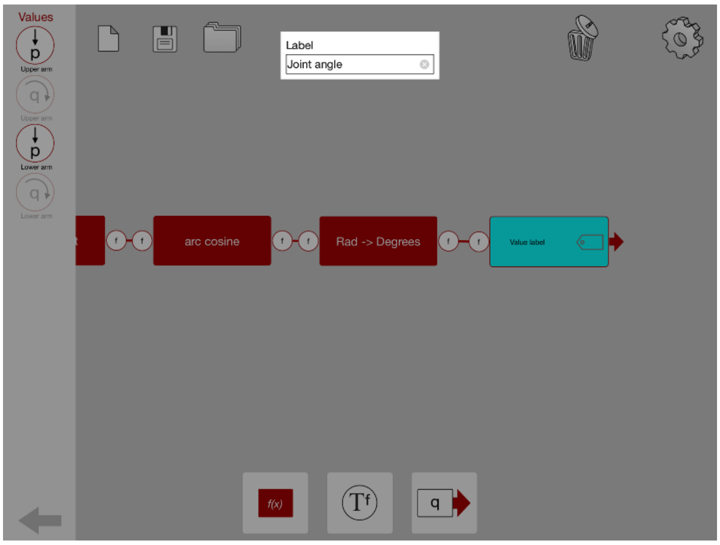
- Perform the same for the Lower arm, by dragging in another red function box, and select the quaternion and vector as the inputs.
- We know the Dot product of two vectors (v_1 and v_2) gives the product of the vector magnitudes and the cosine of the angle (α) between them, with the following formula

$$v_1 \cdot v_2 = |v_1||v_2| \cos(\alpha)$$

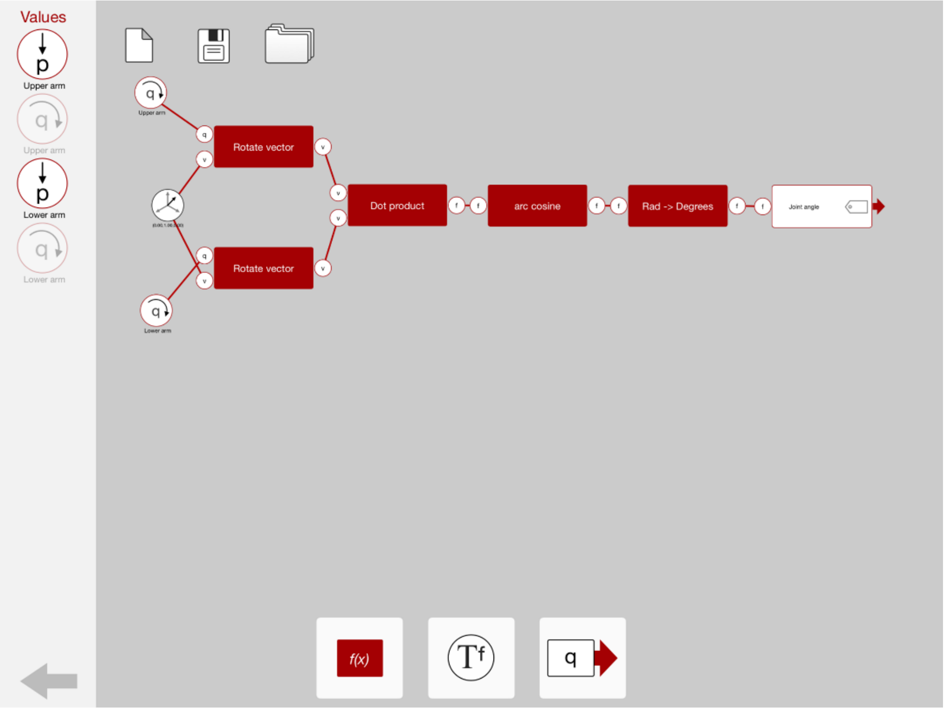
- We can take the Dot product of the two rotated vectors, by putting them as inputs into another function box with Dot product selected. Given that they are unit vectors and their magnitude is equal to 1, the Dot product is equal to the cosine of the angle between them. Therefore, we simply need to just take the inverse cosine of the answer. To do this drag another function box and select arc cosine, the input will be the answer node from the Dot product function.



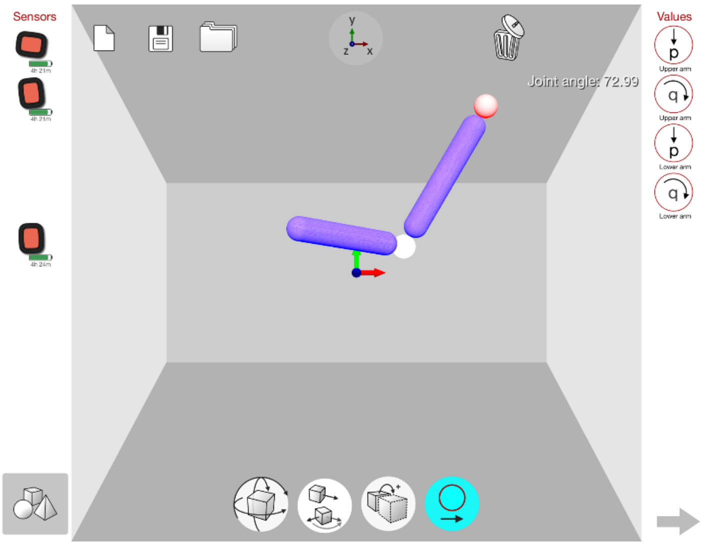
- The answer will be given in radians, if we would like to know the answer in Degrees, we can use another function Rad -> Degrees, simply drag in another function box and select this function. Following this select the answer node from arc cosine and use that as the input node. You have now set up the data flow of calculating a joint angle.
- The answers can be presented as either a label in the model GUI, where the data is printed next to the segments live in real time. We can also stream the data to a third-party device via network stream, if we wish to record the data. For now, we are just interested in showing the angles live in real time. Drag a q rectangle from the bottom next to our final answer and select 'Value Label'. Select this label and click settings to print what the label is, in which we will write 'Joint angle'.


Label
Joint angle

- The final data flow diagram will look like this, you can save this, by clicking the disc button at the top.



- If you now click the Left arrow to go back to the model GUI, we will now see that the joint angles are being shown next to the model in real time.



- You have now created a model tracking your arm movements in real time and showing the angle between them, have a move around and watch the values change.
- The values also have the ability to be streamed to another device. A section within the KineXYZ user-manual gives instructions on how you can do this, if you desire. The data can be streamed as either an .xml or .json file to a device with a known IP address.

2.3 Angular motion and its relationship with linear motion

Purpose
The aim of the following laboratory is to gain an understanding of angular velocity as a derivative of joint angles with respect to time. Furthermore, to understand the relationship between angular velocity and linear velocity.

Task
In the following lab, we will be tasked with determining the angular velocity of the elbow joint and also calculating the linear velocity of the wrist.

Background reading
For background theory refer to angular motion, and relationship of linear and angular motion of the theoretical framework. The graphical user interface of KineXYZ can also be read in the user manual, and also if any functionalities of the software need further clarification.

Equipment

- 2 Xsens DOT sensors
- iPad
- Xsens DOT KineXYZ application
- Tape measure

2.3.1 Part 1: How we calculate the angular velocity from the joint angle

Angular velocity (ω) is a vector quantity that determines the change of angular position with respect to time.

$$\omega = \frac{\theta_{final} - \theta_{initial}}{t}$$

Angular velocity can be presented in degrees per second, however if further calculations need to be performed, the units must be in radians per second, as it is dimensionless. If plotted on an angular position-time curve, angular velocity can be calculated as the first derivative of angular position

$$\omega = lim \frac{\delta\theta}{\delta t} \; as \; \delta t \to 0$$

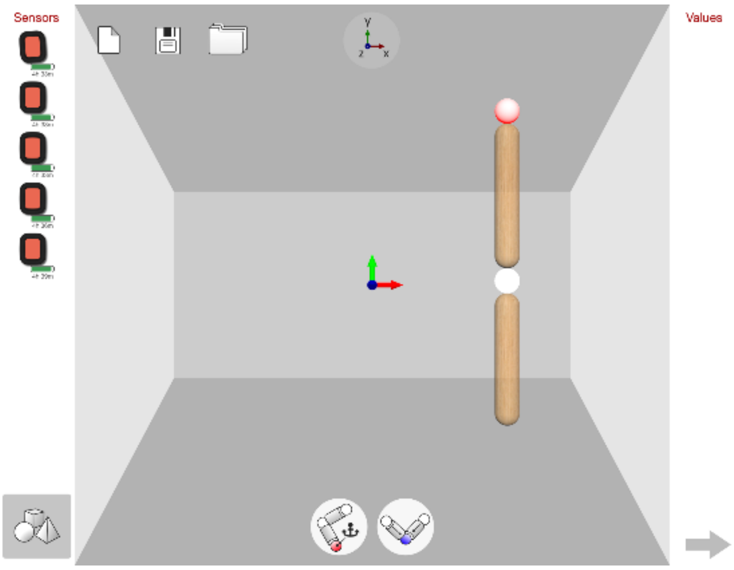
So for instantaneous angular velocity we need to calculate the change of angle between two consecutive time points, or time stamps, that is

$$\omega = \frac{\theta_{t2} - \theta_{t1}}{t_2 - t_1}$$

We have the ability to set this up as a function within KineXYZ.

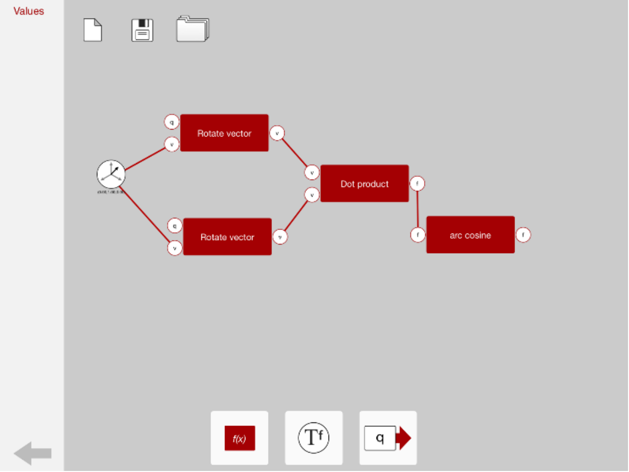
2.3.2 Part 2: Load or Build your Upper arm model

- ➢ You will have an upper arm model already saved from the previous lesson on building a linked segment model, as well as developing a data flow diagram to calculate the elbow joint angle. This can be either loaded, or followed again.

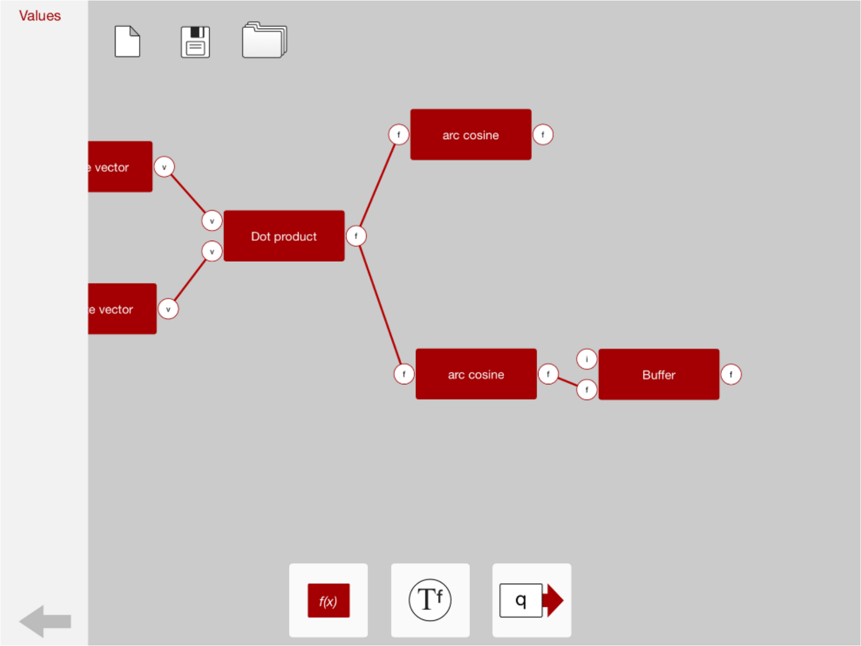


2.3.3 Part 3: Calculating the Angular velocity from the joint angle

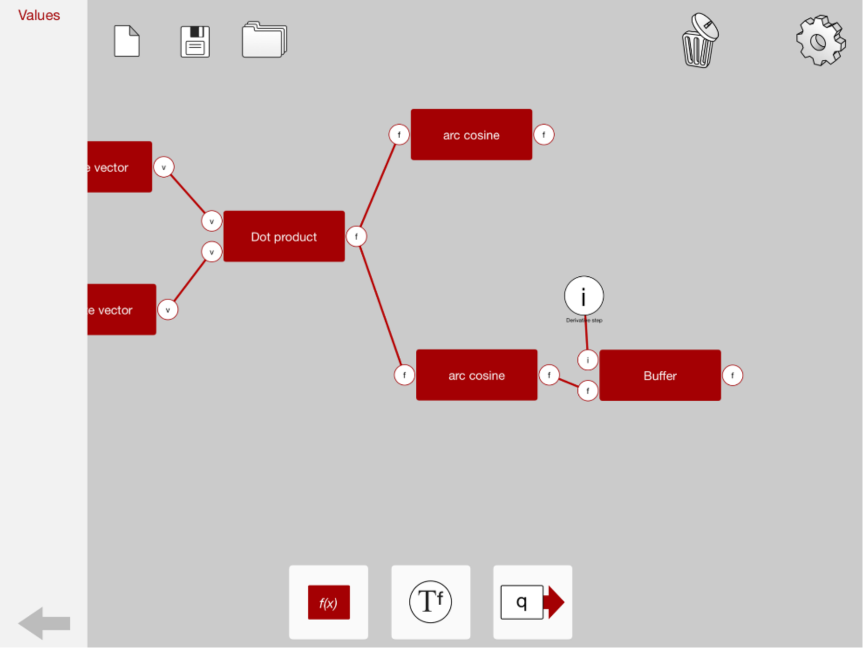
- We will work with radians rather than degrees, as they are dimensionless, and since the angular velocity will be used to calculate the linear velocity later, it is essential that we work with radians. Remove the radians to degrees function that you had originally. Now, you will essentially have the dot product of two rotated vectors and the inverse cosine of that answer.



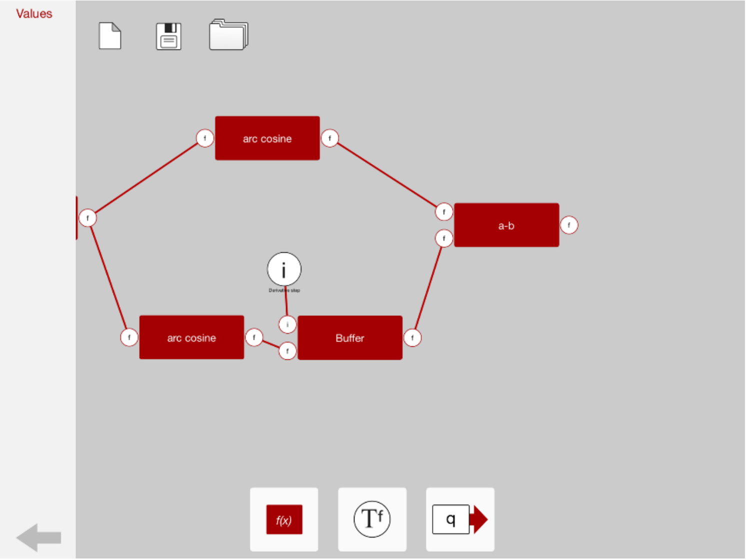
- We are required to calculate the difference between the angle at two time points, so what we will do is set up another arc cosine function from the Dot product function, and attach a Buffer function to it.



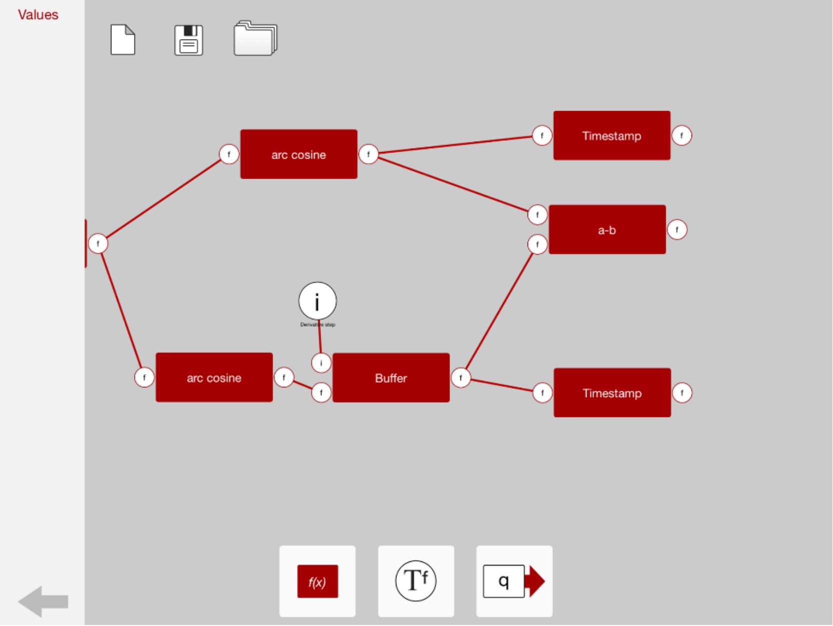
- The Buffer function needs to have an integer value attached to it, to let it know how long between time stamps is needed to collect a value. If we input a value of 1, it will collect the value from the time stamp before the current time stamp. From the T^f button, drag in an integer (i) and assign a value of 1 to it.



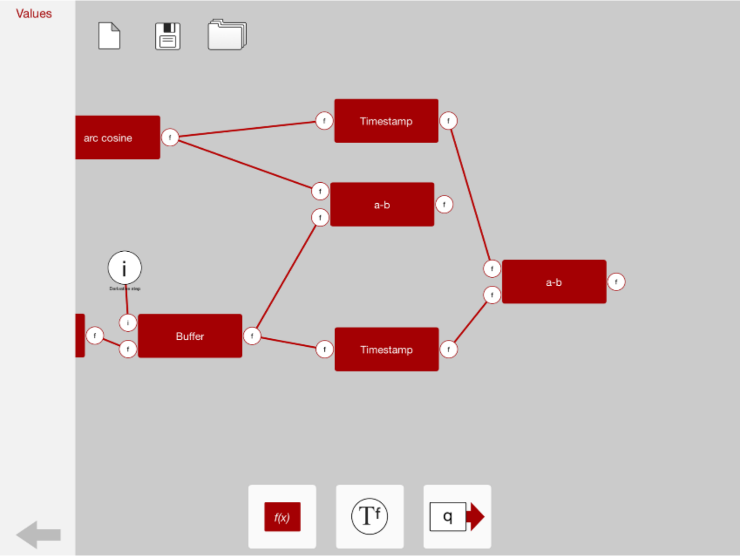
- With this, we can calculate the change in angle from the two time points, drag in another function box, and choose the function (a-b), which calculates the difference between 2 functions. Assign the first or top arc cosine function as the higher input node, and the buffered arc cosine as the lower input node.



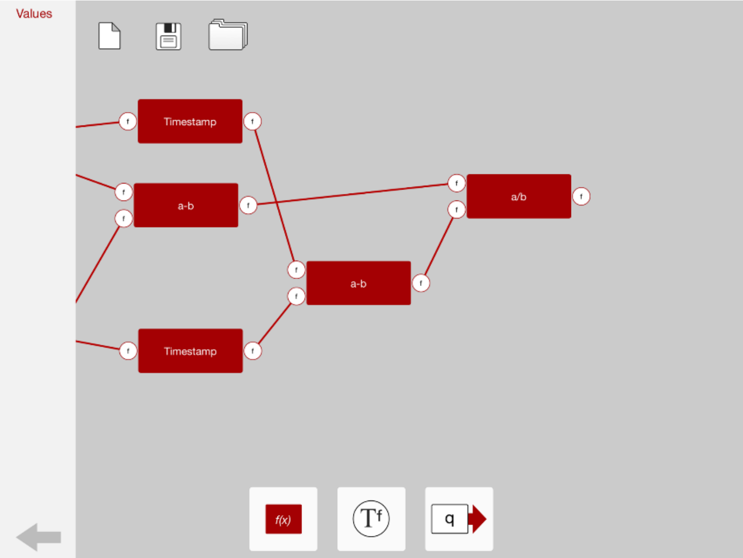
- We have the numerator component of the ω function, to calculate the denominator, we need the time difference, which will be the difference between the two timestamps. To figure out the value of the timestamps, drag a function into the GUI, and choose the Timestamp function, align it with the arc cosine function, which tells what the timestamp value is for that arc cosine value. Repeat the same for the buffered arc cosine function, which will tell you the buffered time stamp.



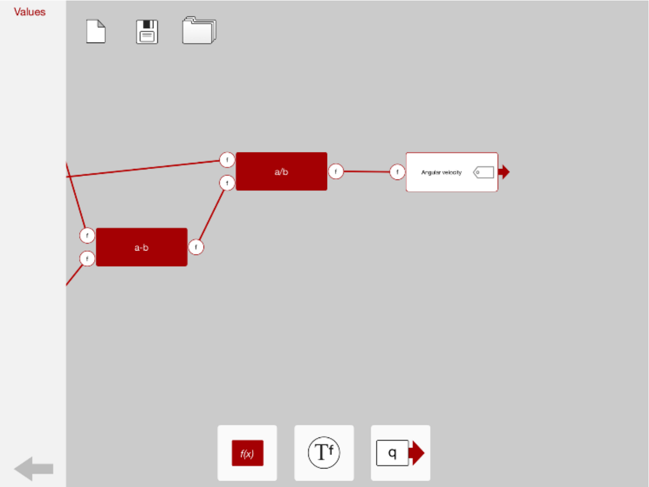
- We now need to know the difference between these two values. Select another (a-b) function, and input the timestamp functions into the receiving nodes.



- This gives us the time difference, and the value of the denominator of the ω function. The next step is to calculate the quotient of the angle difference and the time difference. This can be done with the quotient function (a/b). Drag another function in and choose the (a/b) function. Select the angle difference functions and the time difference functions as the input nodes.



- This value is the angular velocity, which you can now add a label to, name it angular velocity.



2.3.4 Part 4: Calculating the linear velocity of the wrist from the angular velocity of the elbow

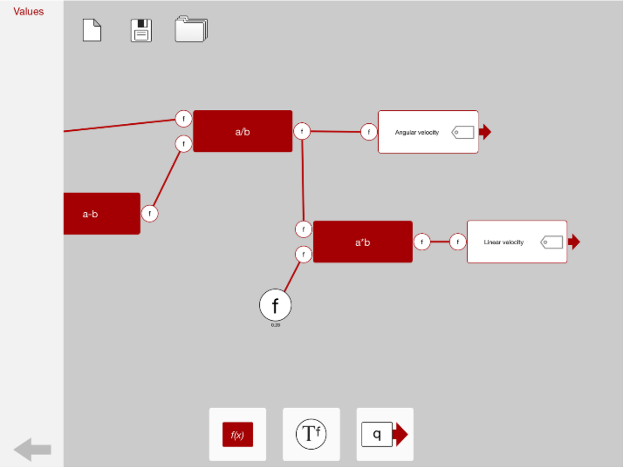
Given that we defined the radian as the angle from which the length of the circles arc is equal to its radius. The length of the arc travelled (s) can be calculated from the angle (θ) and the radius (r) by the equation

$$s = r\,\theta$$

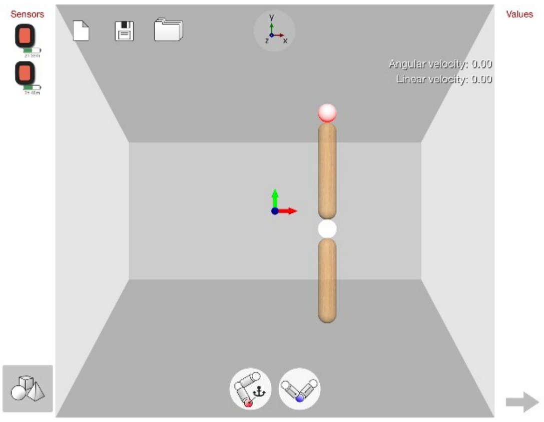
The linear velocity of a point on a rotating body is referred to as the tangential velocity (v_T), which acts as a tangent to the point on the curved path. It is calculated from the angular velocity (ω) and the distance from the centre (r), via the following equation

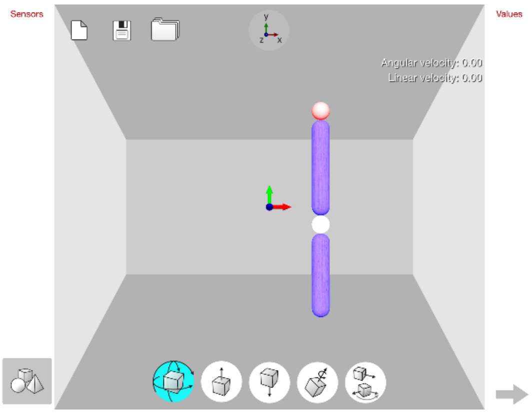
$$v_T = \omega\, r$$

- We have developed the function data flow to calculate the angular velocity, we just need to use the values from this function and multiply the distance of the wrist from the elbow joint, which is the lower arm length. We measured this value to be 28 cm or 0.28m.
- Select a product function (a*b), the first input node will be the angular velocity. From the T^f button, drag in a float number (f) and assign a value of 0.28 to it. Attach a label to your answer, and name it linear velocity.

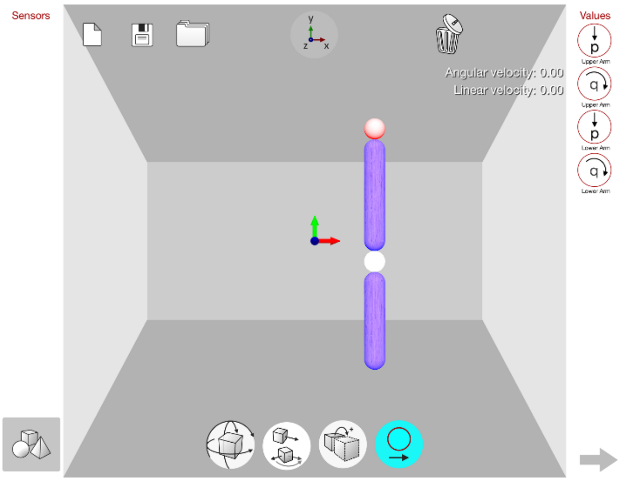


- The data flow is ready, you will need to assign the orientations of your arm segments into the beginning of the data flow. Before we do that, come back to the object window and assign our sensors, following this we will calibrate the sensors to the segments by performing the alignment process.

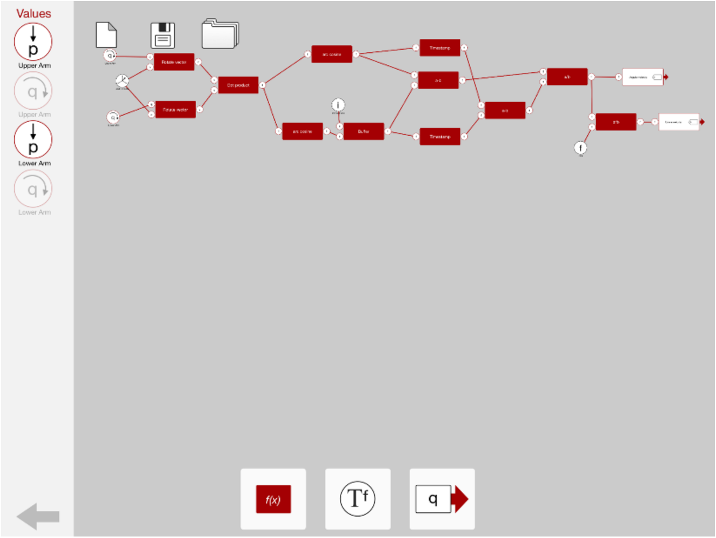




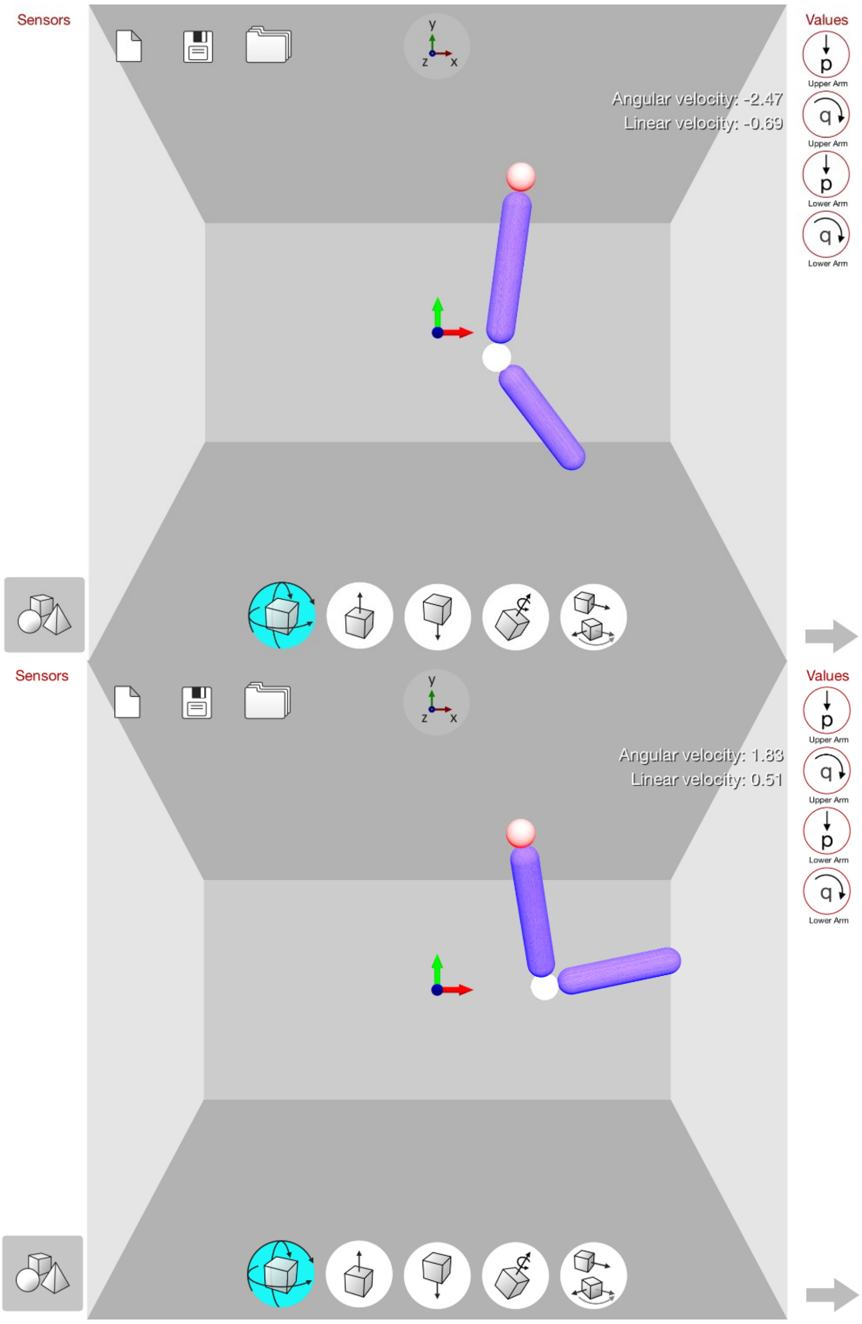
- Once aligned, the object values can be selected to appear in the values column to take back to the data flow diagram window.



- Align the orientations (q) for the upper arm and lower arm to the rotate vector functions at the beginning of the data flow diagram.



- Your model is now ready to show the angular velocity of the elbow and linear velocity of the wrist. Notice how the data changes as you move your hand up and down.



Angular velocity: -2.47
Linear velocity: -0.69

Angular velocity: 1.83
Linear velocity: 0.51

- If you need to record the data, it is possible to set up a network stream to your laptop, you can assign a network stream to any local IP address. Further instructions on how to do this, can be found in the KineXYZ user-manual within the network streamer section.

2.4 Building an upper body model

Purpose

The aim of the following laboratory is to gain an understanding of developing a simplified model of the upper body using some measurements of the participant's anatomy. As well as an understanding of the coordinate systems defined by recommendations of the International Society of Biomechanics (ISB).

Task

In the following lab we will be tasked with forming an upper body model with the Trunk, upper arms and lower arms, using 5 sensors. This is a more simplified model looking at the angles between the trunk and the arms, and does not have a scapula or clavicle. Models including scapula movements such as elevation/depression, protraction/retraction and rotation are much more complex.

Background reading

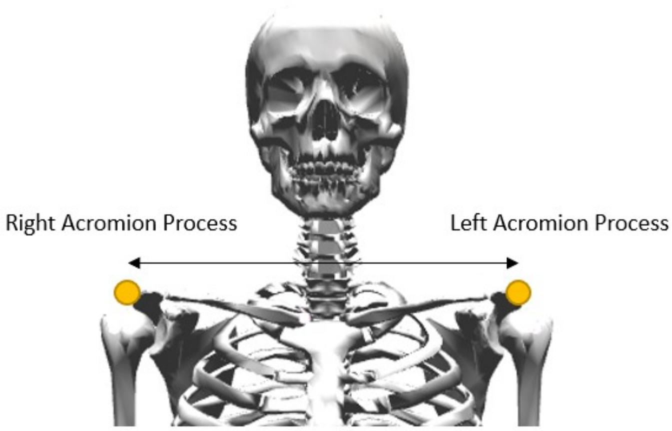
For background theory refer to functional anatomy and inertial measurement units of the theoretical framework. The graphical user interface of KineXYZ can also be read in the user manual, and also if any functionalities of the software need further clarification.

Equipment

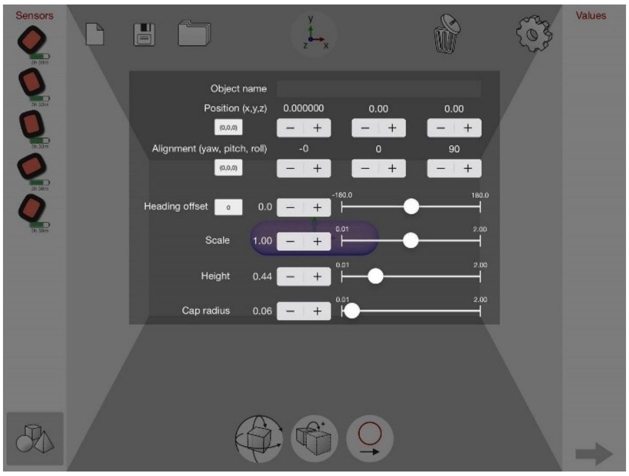
- 5 Xsens DOT sensors
- 5 Straps (1 large, 2 medium, 2 small)
- iPad
- Xsens DOT KineXYZ application
- Segmometer or tape measure

2.4.1 Part 1: Setting up the trunk

- The first thing we will do is set up the trunk or the thorax. We will collect certain anthropometric measurements, remembering that we do not measure positions of anatomical landmarks as we do with optical measurement systems. We take measurements of relevant points as an indication for the scaling of segment lengths. We then use measured accelerations, angular velocities and rotations applied to these segments to estimate positions.
- First you will need to take the following measurements with your tape measure. Identify the acromion process of your participant, by palpating the shoulder, you will feel a bony spike lateral and slightly posterior of the shoulder. Do this for right and left sides, and measure the distance between these two points, from behind the neck, as the points are on the rear side of the scapula. This distance will represent our Shoulder width, make note of this measurement.



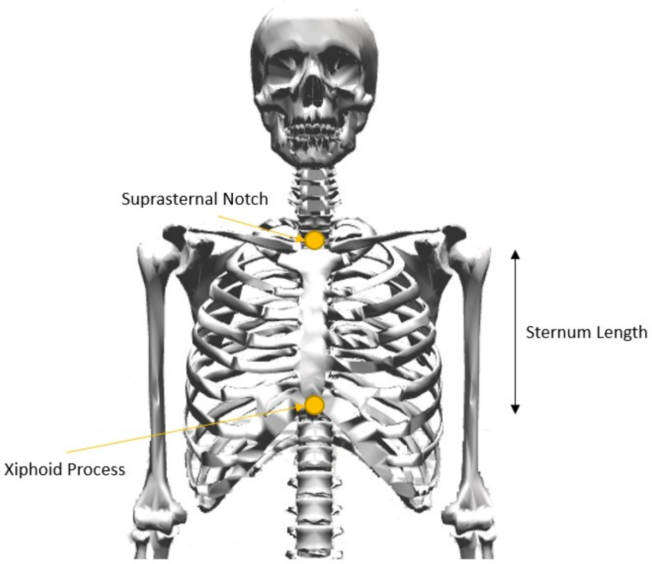
- For the next measurement, identify the most anterior aspect of the right deltoid, as well as the most posterior aspect. Measure the distance between these two points. This will represent our shoulder depth.
- In KineXYZ, press the shape button and drag a capsule into the viewport. Note the direction of the axis, the z axis of the trunk points forward within KineXYZ. The thorax in ISB conventions has the x-axis facing forward. It is always important to check the axes definitions, in order to understand interpretations of joint angles.



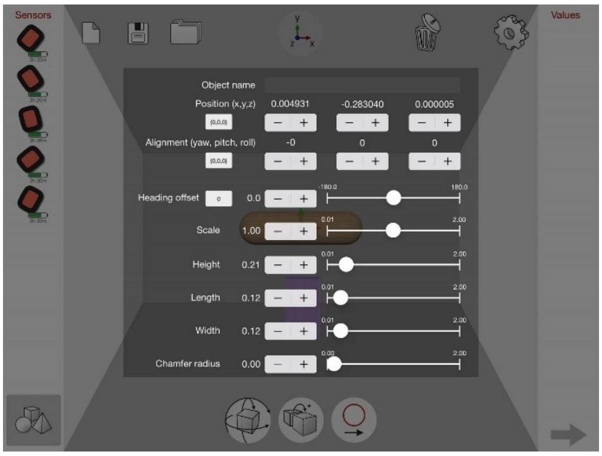
Object name
Position (x,y,z) 0.000000 0.00 0.00
(0,0,0)
Alignment (yaw, pitch, roll) -0 0 90
(0,0,0)
Heading offset 0 0.0 -180.0 180.0
Scale 1.00 0.01 2.00
Height 0.44 0.01 2.00
Cap radius 0.06 0.01 2.00

- Select the capsule so that it is highlighted, and click on the settings button. No need to name the object yet, because we are planning to fuse another object to it. We would like the capsule to be horizontal because it is representing the inter-acromion distance, you can do this by rotating it 90 degrees in the roll column. Set the origin of the object to (0,0,0), input half of the shoulder depth measurement that you took into the cap radius section (the whole value would be the diameter not radius), and input the trunk width measurement you took into the height. Your box will now look more like a wide rectangle now, you can rotate the viewport to look at it front on.

- Next, we will build a sternum component to fuse onto this, as this is where the sensor will be attached. For this you will need to locate the suprasternal notch, this is the point at the top of the sternum and where the two collarbones meet, make note of this point. Next, locate the Xiphoid process, which lies at bottom of the sternum. Make note of this measurement.

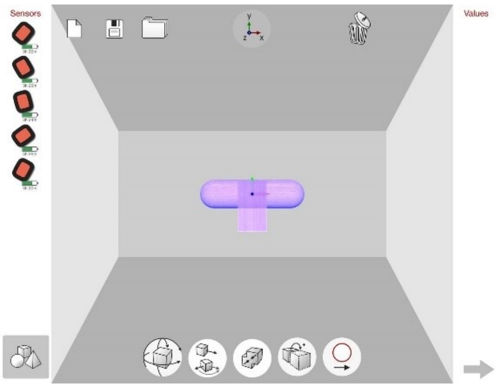


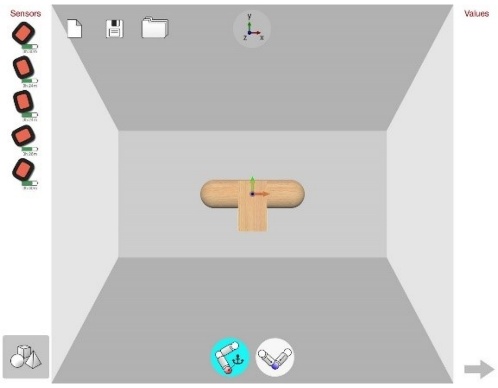
- Drag a new box into the viewport, and under its settings, input the sternum length you measured into height, and the shoulder depth measurement into the length and width. You will not need to name the object as we will be fusing this segment to the trunk section, this can be done, by either manually moving it into place, or adjusting the origin settings, by inputting the origin as (0,0,0), and moving it such that it is in the middle of the trunk, with the anterior and superior surfaces aligned.



Object name
Position (x,y,z) 0.004931 -0.283040 0.000005
Alignment (yaw, pitch, roll) -0 0 0
Heading offset 0 0.0
Scale 1.00
Height 0.21
Length 0.12
Width 0.12
Chamfer radius 0.00

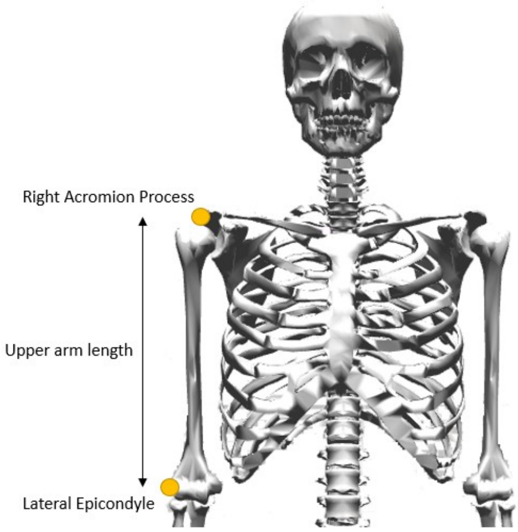
- To fuse the two segments, select them both, and click the combine button, which looks like two cubes joining together. Select the new fused object, and click settings, as you will need to name it. Name it Trunk.



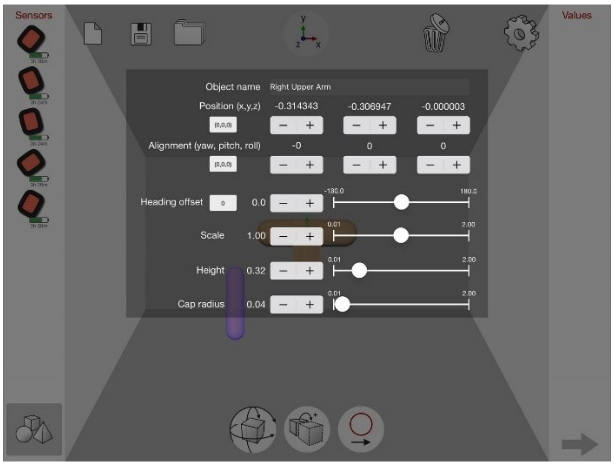


2.4.2 Part 2: Setting up the arms

- To set up the arms, we will first begin with the upper arm. On your participant locate the acromion process again on the right shoulder. Following this, locate the lateral epicondyle of the right humerus, which is the bony protuberance you feel on the outside of the elbow. Using the tape measure, measure the distance between these two points, this will be the right Upper arm length.

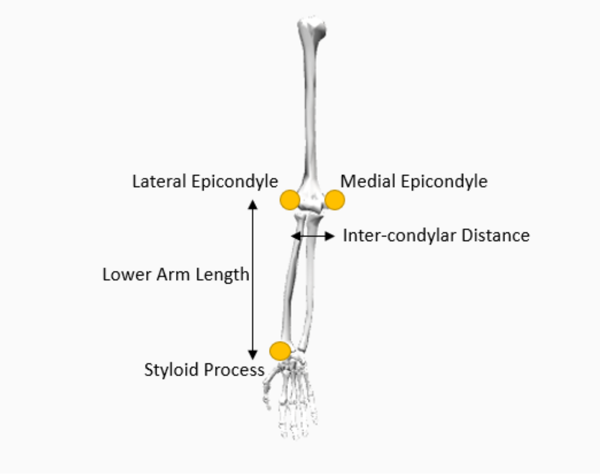


- Along with this, also locate the medial epicondyle of the humerus, the bony protuberance you feel on the inside of the elbow. Using your tape measure, measure the distance between the medial and lateral epicondyles. This distance will be the intercondylar distance of the elbow.
- Within KineXYZ, open the shapes tab, and select a capsule, second from the left, within the settings, name this object Right Upper arm. Adjust the height of the capsule to be the Upper arm length measured. Adjust the cap radius to be half of the intercondylar distance you measured.

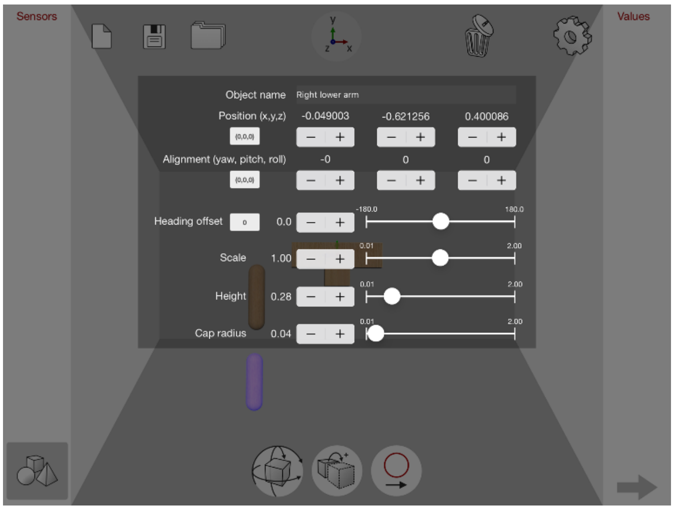


Object name Right Upper Arm
Position (x,y,z) -0.314343 -0.306947 -0.000003
Alignment (yaw, pitch, roll) -0 0 0
Heading offset 0 0.0
Scale 1.00
Height 0.32
Cap radius 0.04

- ➢ Next locate the styloid process of the radius, found on the lateral side of the wrist, if the palm is facing forward. Measure the distance between the lateral epicondyle of the humerus, and the styloid process of the radius. This distance will be the lower arm length.



- ➢ Create another capsule from the shapes menu, name the object right lower arm. Input the height as the lower arm length, and the cap radius as half of the elbow intercondylar distance you measured.



Object name: Right lower arm

Position (x,y,z): -0.049003, -0.621256, 0.400086

Alignment (yaw, pitch, roll): -0, 0, 0

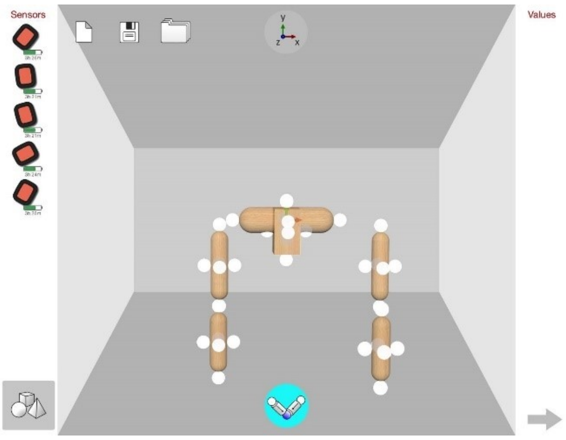
Heading offset: 0.0

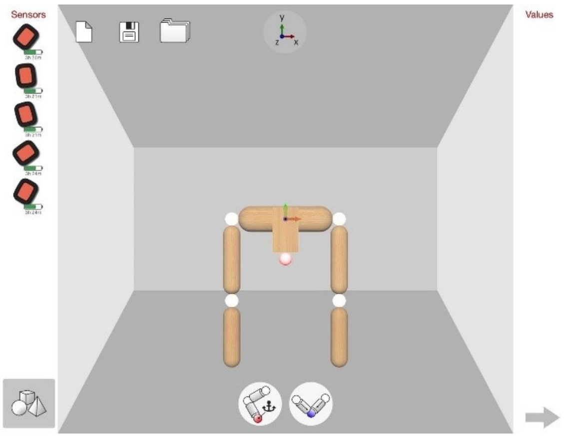
Scale: 1.00

Height: 0.28

Cap radius: 0.04

- ➢ Repeat the same process to create a left upper arm and a left lower arm, you can simply use the same measurements you took on the right side, and name them appropriately.
- ➢ Now select the joints button, and highlight the relevant points to join the segments. Align the proximal end of the lower arm with the distal end of the upper arm, and the proximal end of the upper arm with the shoulder, you will see the joints highlighted as blue, when you select them. Set the anchor point to be at the bottom of the trunk.

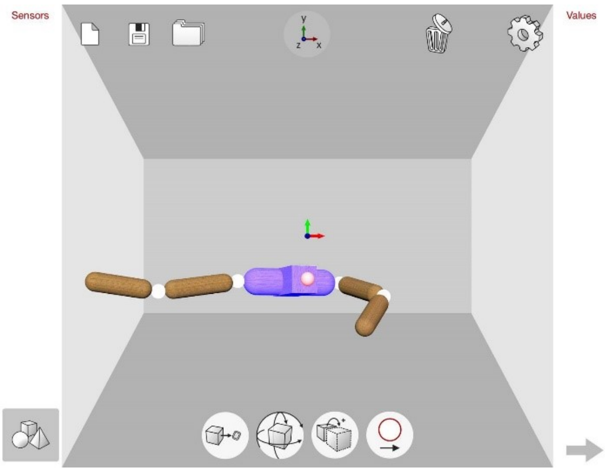




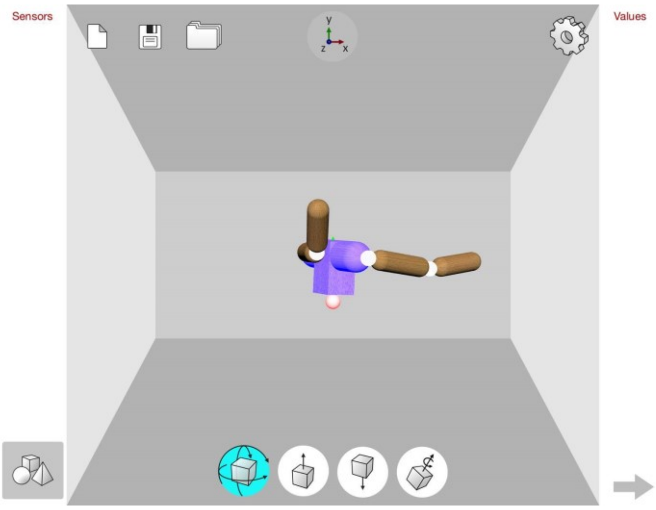
- ➢ Your upper body is constructed and will now be ready for sensor allocation and calibration. You can also save it if desired.

2.4.3 Part 3: Sensor placement & alignment

- ➢ Ensure the sensors are switched on, detected and aligned by pushing the heading reset button with the sensors in a known direction.
- ➢ Next you will need to identify which sensor is which, by rotating it about the sensor y axis, so you know which sensor to assign to each corresponding segment before placing it on the body. Once you have established this, drag the sensor onto the respective body segment.

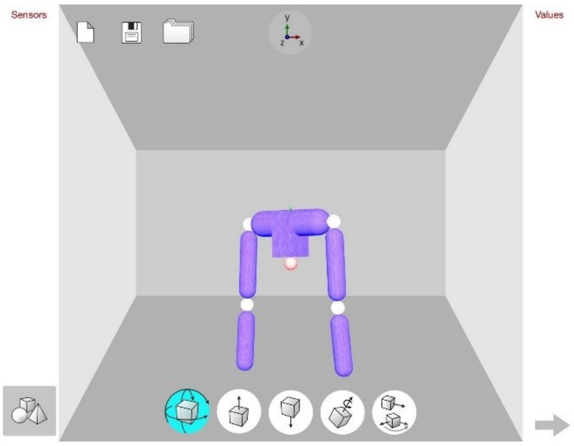


- Place the trunk sensor onto the body or flat section of the sternum at the front of your chest. The sensor can be place in the pocket of the large strap and wrapped around the body with Velcro to hold in place.
- The upper arm is placed midway on the upper arm, between the bicep and triceps muscle on the lateral side.
- The lower arm sensor is placed just below the wrist on the dorsal (rear) side of the forearm.
- Once all sensors have been placed on their segments, your model will likely look in a very odd and non-anatomical arrangement. This is because they have not been calibrated and aligned to their respective segment.



- Select just the trunk segment, have the participant stand upright, and click the vertical alignment button. Next lean forward with the trunk to detect the forward detection and click the horizontal alignment button.

- Following this, select all of the segments of the upper body by double clicking the torso. Then press the vertical alignment button.



- Also lift your arms by your side to see if any further horizontal alignment is needed for the arm segments, which can happen. Look at the model from a superior view, with your arms held out, if two particular segments do not line up, you can select them, and click heading reset, the lower segment will match the heading of the upper segment.
- Your upper body model is now ready for use.

2.5 Building a lower body model and estimating the hip joint centre with regression techniques

Purpose
The aim of the following lesson is to gain an understanding of building a lower limb model, as well as using Harrington regression equations to estimate the hip joint centre.

Task
In the following lesson we will be tasked with building a lower limb model with 5 sensors, and using Harrington regression to estimate the hip joint centre.

Background reading
For background theory refer to functional anatomy and coordinate systems in the theoretical framework.

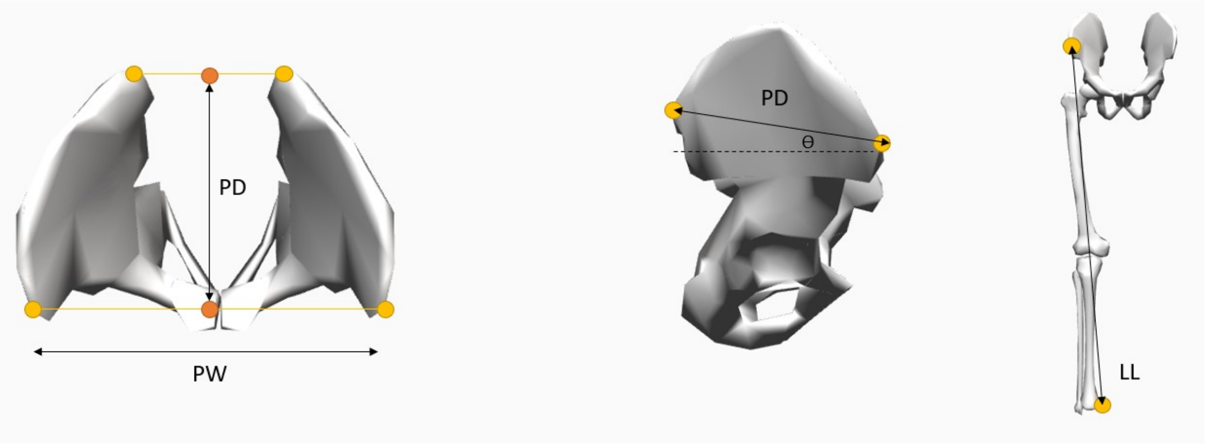
Equipment

- 5 Xsens DOT sensors
- iPad
- KineXYZ application
- Segmometer or tape measure

2.5.1 Part 1: Estimating the hip joint centre

The first step is to create a model for the pelvis and roughly estimate where the hip joint centre would be using Harrington regression. To do this, we first need to take a few measurements of the participant in accordance with Harrington et al. (2007)[17]. First, we need to collect the following measurements.

Pelvis Width (PW): The distance between the right and left ASIS points, these are the bony protuberances you feel at the front of your hips.
Pelvis Depth (PD): The mid-point of a line drawn between left and right ASIS points, will be the mid ASIS point. The mid-point of a line drawn between the left and right PSIS points (the bony protuberances felt at the back of your hips) will be the mid PSIS point. The distance between these two mid-points is the Pelvis depth.
Leg Length (LL): The distance from the ASIS to the medial malleolus of the ankle (the bony protuberance on the inside of your ankle).



Pelvis measurements to estimate the location of the hip joint centre according to Harrington et al. (2007). The left picture is an axial view of the pelvis, with the anterior pointing downward. The middle picture is a sagittal view of the pelvis, with the anterior pointing right. The right picture is a frontal view of the pelvis and right leg.

It is very important to note the following, the regression equations are according to ISB axes definitions, the z axis moves between right and left ASIS, the x axis lies along the plane containing mid PSIS and mid ASIS, with the y axis is orthogonal to those. This is different to the axis definitions in KineXYZ, so we will need to remember this when we build the object in KineXYZ.

When you have made the measurements of the pelvis width, pelvis depth and leg length, input them into the following formulas, this will give the location of the right hip joint centre with respect to the midpoint of left and right ASIS, in millimetres.

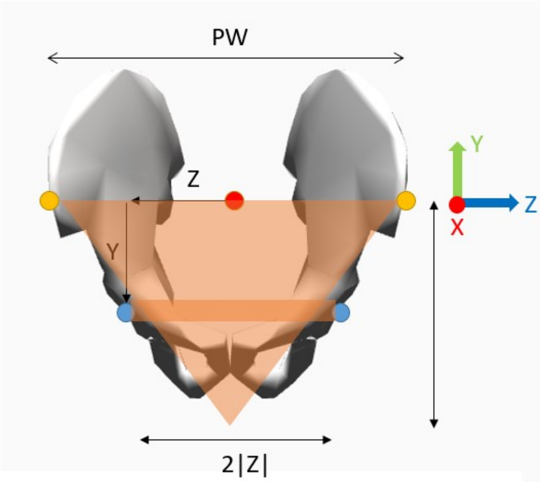
X (Anterior/Posterior) => -0.24(PD) – 9.9
Y (Superior/Inferior) => -0.16(PW) – 0.04(LL) – 7.1
Z (Medial/Lateral) => 0.28(PD) + 0.16(PW) +7.9

For example, someone with PW = 260mm, PD = 170mm, LL = 840mm, would calculate the following location of the right hip joint centre
X (Anterior/Posterior) => -50.7mm
Y (Superior/Inferior) => -82.3mm
Z (Medial/Lateral) => 97.1mm

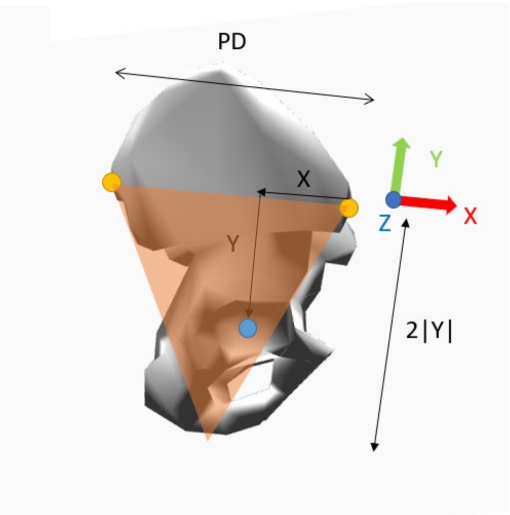
These values are from the middle of the line connecting the two ASIS points

2.5.2 Part 2: Building the Pelvis model

- By taking this point calculated as the hip joint centre, we would see it with respect to the mid ASIS origin located like this, with respect to an ISB axis definition.



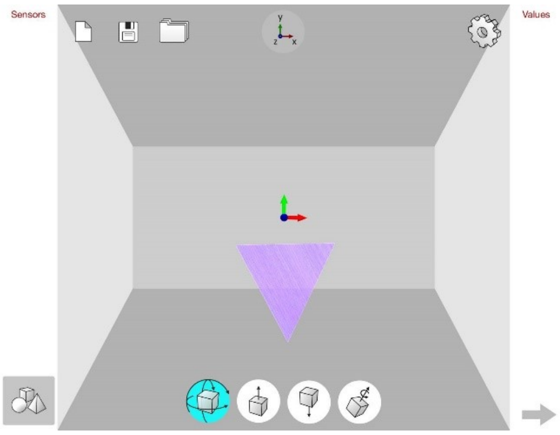
Frontal view

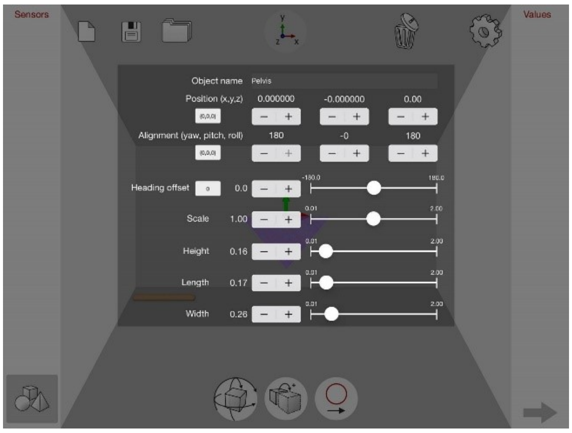


Sagittal view

- We will begin by building an upside-down pyramid, the flat surface of this will be tilted depending on the degree of tilt of the pelvis, which we will calculate as the angle between the horizontal and the line joining mid ASIS and PSIS. We will fuse a bar to this pyramid, which joins together the two hip joint centres, its position will be known with respect to the mid-ASIS point.

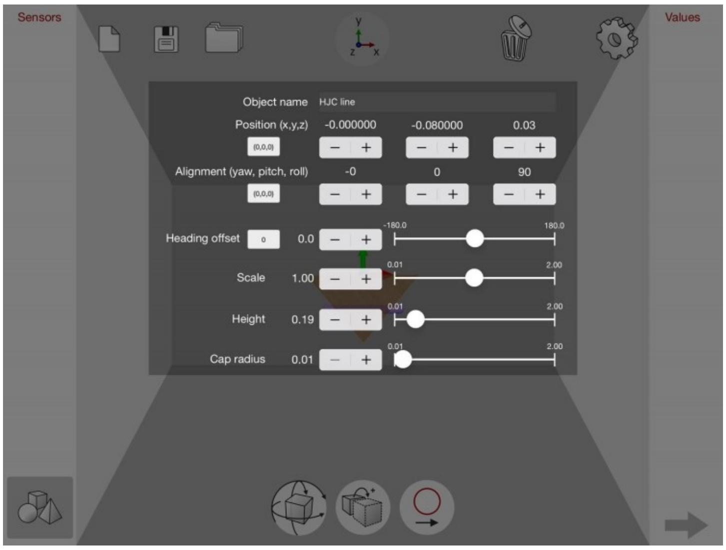
- The pyramid will have a width of the Pelvis Width, a height 2 times the absolute value of Y (164.6mm), and a length or depth of the Pelvis Depth. with the HJC located half way between the height, and half way between the length. We will create a pyramid within KineXYZ, with these dimensions (note: KineXYZ only works in metres to 2 decimal places, so you will have to round to the nearest decimal).





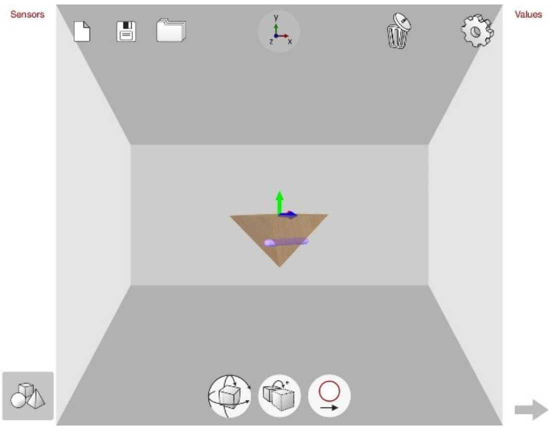
Object name Pelvis
Position (x,y,z) 0.000000 -0.000000 0.00
Alignment (yaw, pitch, roll) 180 -0 180
Heading offset 0.0
Scale 1.00
Height 0.16
Length 0.17
Width 0.26

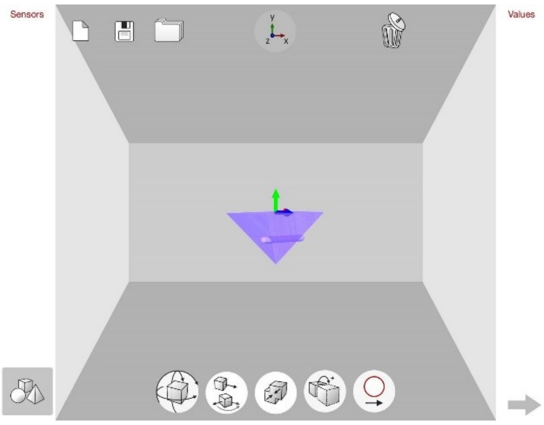
- Set the origin of the pyramid to (0,0,0) to make it easier to place the bar with the hip joint centres.
- Next drag in a capsule, and rotate it 90 degrees so that it is sideways, set the cap radius to be the minimum 0.01. Set the height of it to be double the medial/lateral value of the hip joint centre location (Note, we are in KineXYZ now where the axis definitions are different).



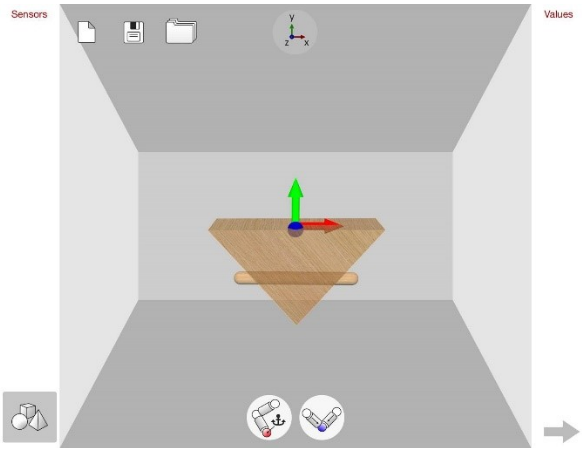
Object name HJC line
Position (x,y,z) -0.000000 -0.080000 0.03
Alignment (yaw, pitch, roll) -0 0 90
Heading offset 0.0
Scale 1.00
Height 0.19
Cap radius 0.01

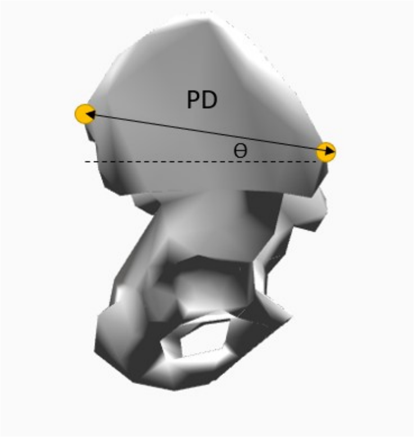
- Use the superior/inferior and the anterior/posterior values to determine where the bar should be with respect to the origin of the pyramid which you set at (0,0,0).





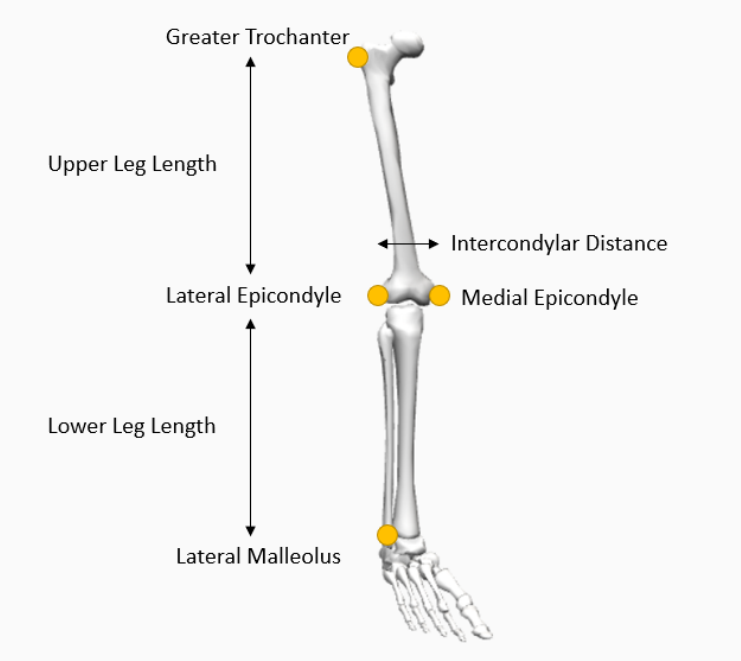
- Select both objects and fuse them together.
- Now that they are fused, you can place a forward tilt on the object to correspond with the degree of pelvic tilt. This angle of tilt can be measured or alternatively estimated. A study of an asymptomatic group found on average this angle between the pelvis depth line and the horizontal to be roughly 6 degrees tilted downward[18]. One must proceed with caution if just using an estimate, as individuals may have excessive anterior or posterior tilt. The amount of pelvic tilt can be due to several factors including pelvis geometry, the degree of lumbar lordosis, and the balance of different muscle groups.



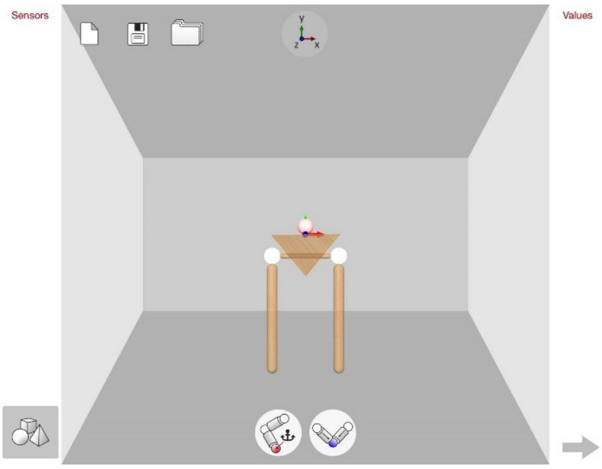


2.5.3 Part 3: Building the Legs

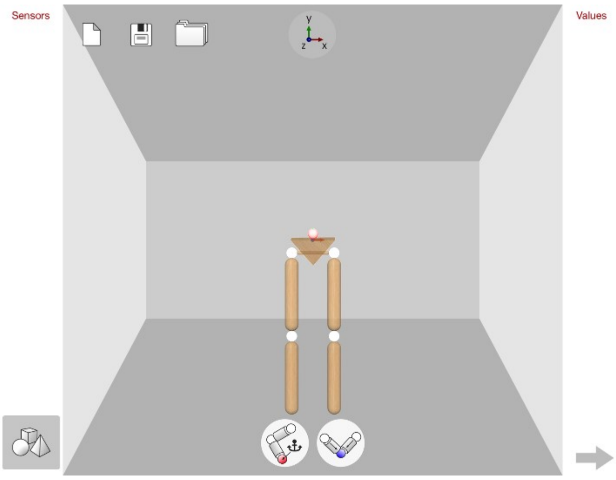
- Next, we will need to take some measurements for the leg lengths. Identify the Greater Trochanter and Lateral Epicondyle of the femur, and measure this distance. This will be known as the Upper Leg length.
- Also measure the distance between the Lateral and Medial Epicondyle, this will represent the intercondylar distance.



- To build the Upper legs, select a capsule. Input the height to be the Upper Leg Length, and the cap radius to be half of the Intercondylar Distance. Following this you can form joints with the Pelvis.

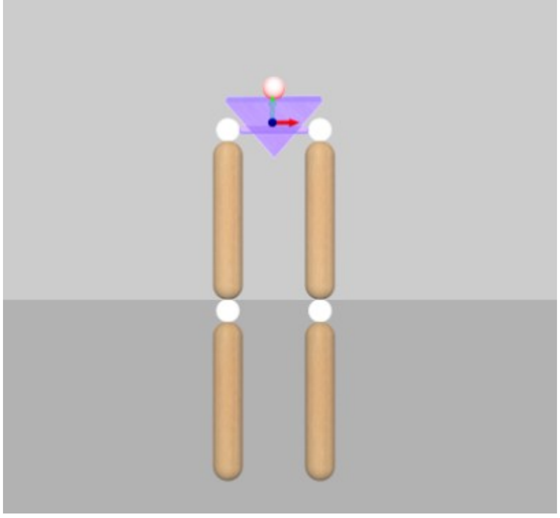


- Next, make note of the Lateral Epicondyle of the femur, and the Lateral Malleolus of the ankle joint. Measure this distance. You can create a capsule for these also, with height the Lower Limb length and have the cap radius as half of the intercondylar distance. Following this, you can form joints with the Upper legs.



2.5.4 Part 4: Alignment

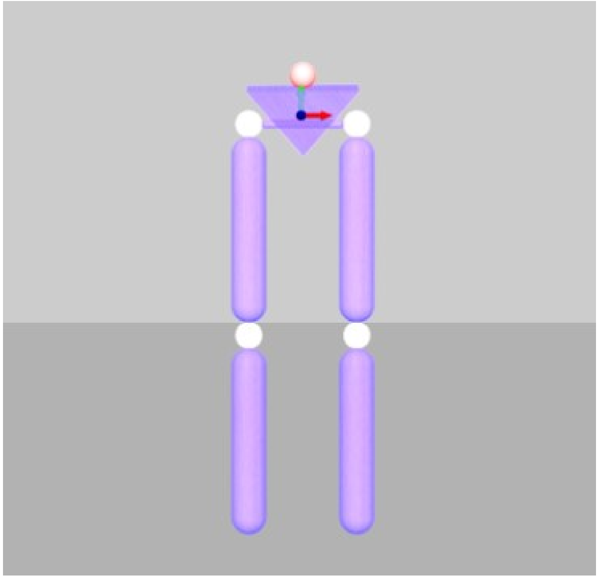
- Ensure the sensors are switched on, detected and aligned by pushing the heading reset button with the sensors in a known direction.
- Next you will need to identify which sensor is which, by rotating it about the sensor y axis, so you know which sensor to assign to each corresponding segment before placing it on the body. Once you have established this, drag the sensor onto the respective body segment.
- Place the Pelvis sensor onto the Sacrum, in between the two PSIS. The sensor can be place in the pocket of the large strap and wrapped around the body with Velcro to hold in place.



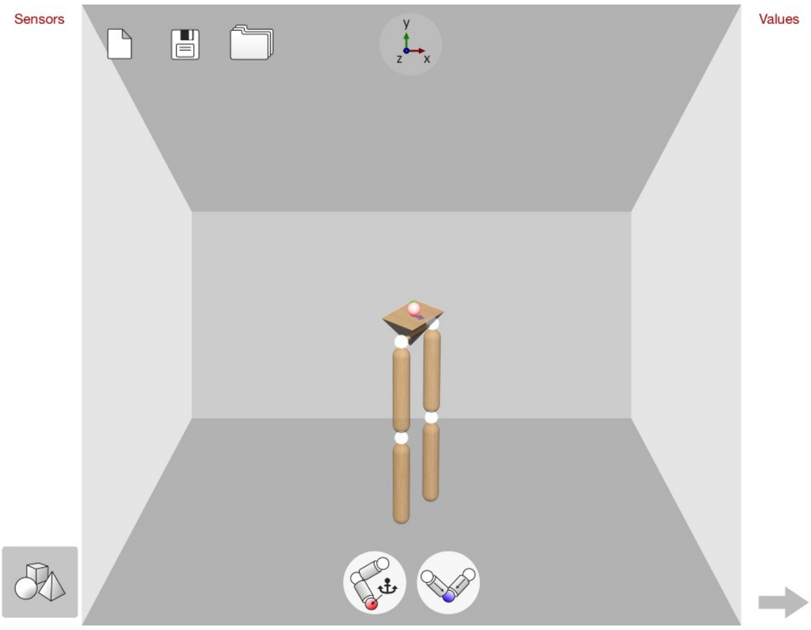
- The upper Leg is placed midway on the leg, between the quadricep and hamstring muscles on the lateral side.
- The lower leg sensor is placed on the flat of the antero-medial surface of the Tibia.
- Once all sensors have been placed on their segments, your model will likely look in a very odd and non-anatomical arrangement. This is because they have not been calibrated and aligned to their respective segment.

- Select just the Pelvis segment, have the participant stand upright, and click the vertical alignment button. Next lean forward to detect the forward detection and click the horizontal alignment button.

- Following this, select all of the segments of the lower body by double clicking the Pelvis. Stand in a completely neutral pose, attempting to be completely straight at all of the segments. Then press the vertical alignment button.



- Your Lower body model will now ready for use.



2.6 *Biomechanical approach applied to sprint mechanics*

Purpose
The aim of the following laboratory is to apply the lessons we have learnt in the biomechanical approach to analysing human movement. When analysing a skill, one must list the mechanical features that contribute to a given skill and be able to collect, analyse and interpret the data. This establishes characteristics and allows appropriate interventions to be designed.

Task
In the following lab we will be tasked with analysing some parameters involved in sprint mechanics, using our model for approaching human movement analysis. The process may also be repeated for other skills or tasks.

Background reading
For background theory refer to functional anatomy and kinematics of the theoretical framework, specifically biomechanical approach to motion analysis.

Equipment

- 5 Xsens DOT sensors
- 5 sets of straps
- Running shoes
- iPad
- KineXYZ
- 2 Cones/witch-hats
- Tape measure

2.6.1 Step 1: Preparation

This involves breaking down and identifying the different phases of movement in the task/skill, as well as identifying the critical variables involved in each phase. For the sprint performance, with your group discuss some mechanical features that make up the skill with respect to technique and discuss what is ideal[19]. For each mechanical feature, discuss which plane of motion is ideal to investigate and which anatomical movements are involved.

Mechanical feature	What is ideal
Head position	- The head should be neutral and in line with the trunk, and trunk in a straight line with legs (when legs at full extension). - Head must not sway or bounce in any direction
Trunk posture	- During acceleration, the trunk has a more pronounced lean forward (around 45° optimal) to aid in overcoming inertia. - Once maximum speed has been reached, the trunk has a more erect posture (Around 80° optimal) and in a straight line with legs at full extension.
Leg action in swing	- The knee rises up and the thigh becomes nearly parallel with the ground, with the foot in a dorsi-flexed position.
Leg action in propulsion	- The hip, knee and ankle extend in a coordinated fashion. - The foot must not be placed in front of the body when contact occurs with the ground, but right underneath. - A straight line must be achieved through the trunk, hip, knee and ankle when at full extension, prior to foot leaving the ground. - The heel of the foot then kicks up towards the buttocks
Arm action	- Very large rotational forces are generated from the lower limbs, strong movements of the arms are needed to counteract these in a coordinated fashion to keep the body in alignment. - Arm should move as a whole unit, without undergoing excessive flexion or extension at the elbow. Try to keep the elbow bent around 90°. - Arm movement should only be forward and backward, and never side to side.

Mechanical feature	Anatomical movement and plane of motion
Head position	Cervical flexion/extension (sagittal plane)
Trunk posture	Trunk flexion/extension (sagittal plane)
Leg action in swing	- Hip flexion/extension (sagittal plane) - Knee flexion/extension (sagittal plane) - Ankle dorsiflexion/plantarflexion (sagittal plane)
Leg action in propulsion	- Hip flexion/extension (sagittal plane) - Knee flexion/extension (sagittal plane) - Ankle dorsiflexion/plantarflexion (sagittal plane)
Arm action	- Shoulder flexion/extension (sagittal plane) - Shoulder abduction/adduction (coronal plane) - Elbow flexion/extension (sagittal plane)

2.6.2 Step 2: Observation

- ➢ Using the cones and tape measure, set up a distance of 40 metres (if you don't have a tape measure, simply measure 40 stride lengths).
- ➢ Within your different groups, choose one of the mechanical features to investigate.
- ➢ Prior to data collection, ensure a warm up and stretch is done for the people undergoing data collection, as they are performing a maximum speed drill.
- ➢ Connect the sensors on the KineXYZ app on the I-Pad
- ➢ Place the Xsens DOT sensors on the corresponding body segments you wish to measure.
- ➢ Load the desired body segment-model.
- ➢ Measure the segment lengths of the desired body segments, and input into the model's segment information.
- ➢ Align and calibrate the sensors with the subject standing in a neutral pose.
- ➢ Select the relevant model for collection of the desired joint angle.
- ➢ Whoever is recording from the I-Pad should stand at the halfway mark of the allocated sprint distance, to ensure they are within range of the sensors throughout each trial.
- ➢ Pressing record, instruct your participant to sprint the 40m as fast as they can. Once they have completed the distance, you can stop recording.

2.6.3 Step 3: Evaluation/Diagnosis

- ➢ Compute the desired joint angles that comprise the mechanical feature you chose and input it into the table below.
- ➢ Next, compare the measured joint angles from your chosen mechanical feature to what is ideal and include a range of acceptability (ie. 5-10°) to establish whether it was achieved.

Mechanical feature	Result	Ideal	Range	Comments

2.6.4 Step 4: Intervention

You have now taken a measurement of a critical variable of interest for achieving sprint performance, as well as a comparison to what is ideal. You now have the information needed to determine if any interventions are needed to optimise the desired mechanical feature. Remembering from our theory of intervention. Interventions can be in the following forms

- Technical: This may involve changes to the technique of the task/skill
- Physical: This may involve improving the physical aspects of the task/skill by addressing a given weakness via appropriate strength or conditioning training.
- Psychological: Addressing any potential psychological fears towards a task or skill, this may be present returning from injury.

Given, we were measuring features of their technique. What technical changes would you recommend your participant undertake, based on the evaluation of their performance?

3 Field based Assignment: Putting it all into practise

3.1 Purpose

Upon completion of the relevant sections of theoretical framework, as well the completion of the practical lessons using inertial measurement units and the KineXYZ application, students can now put it all into practice by undertaking a field-based assignment.

It is essential for practitioners to have the skills to collect, analyse and present data. This assignment is designed to reinforce understanding and to help students gain confidence with Biomechanics and STEM concepts.

3.2 Task

The task is to prepare a written report, that introduces a critical variable/parameter of interest related to improving performance or mitigating injury risk. Students will be required to work together in groups using the biomechanical approach we have learned. This will teach skills of experiment design, data collection, analysis, discussing findings and recommending improvements.

3.3 Choose a skill

Students can choose a skill from any of the following sports. Students are also free to analyse anything of their choosing, if they feel it is an activity or task that could have any potential to improve performance or mitigate injury risks. It doesn’t necessarily need to be a sport either, Biomechanics is also applied to clinical and workplace settings.

- Australian football
- Badminton
- Basketball
- Cricket
- Hockey
- Netball
- Rugby
- Soccer
- Tennis
- Volleyball

3.4 Outline of report

- Introduction of topic: Introduce what you as a group are planning to investigate, and why it is of importance. You should review any relevant literature around the critical variable of interest you plan to research to help you determine what is ideal.
- Methods: Describe all of the procedures you performed to acquire your data. Be descriptive enough so that someone could repeat your experiment.
- Results and Discussion: Present the data of your observations, and evaluate it against what it should be. Give discussion of your findings.
- Conclusion: Summarise your findings and discuss any interventions you would recommend.

3.5 Assessment criteria

Introduction

Excellent	Proficient	Poor
Thoroughly but concisely presents main points of introduction in a well-organised manner.	Adequately presents main points of introduction in a fairly well-organised manner.	Does not sufficiently present main points of introduction, and is not well-organised.

Methods

Excellent	Proficient	Poor
Methods and procedures are fully documented such that the study can be replicated in its entirety. Presentation order and flow is logical, clear and well organised.	The majority of methods and procedures are documented such that the study can be partially replicated. Presentation order is mostly logical with adequate flow	Limited and inappropriate methods are presented. There is no logical flow to the order of presentation

Results and discussion

Excellent	Proficient	Poor
Key/critical results presented. Excellent use of graphs and tables, all presented in a logical order. Results presented have clear link to the research question. Excellent discussion of results with logical flow and clear linkage to introduction and relevant literature.	Key/critical results presented. Adequate use of graphs and tables, all presented in a logical order. Results are linked to the research question. Adequate discussion of results with acceptable flow and linkage to introduction and relevant literature.	Key/critical results are missing. Inappropriate use of graphs and tables though errors may be present. Poor/no linkage to the research question. Inappropriate discussion of results with no flow and linkage to introduction and relevant literature.

Conclusion

Excellent	Proficient	Poor
Key/critical findings are clearly and succinctly summarized. Scientific and practical recommendations linked to findings are presented.	Key/critical findings are summarized though some may be missing. Scientific and practical recommendations presented.	Few or no key/critical findings presented. Few/none/ inappropriate scientific and practical recommendations presented.

4 Educational Outcomes achieved for Australian Tertiary Admission Rank (ATAR)

4.1 Physical Education Studies

General course overview

In the Physical Education Studies ATAR course students learn about physiological, psychological and biomechanical principles, and apply these to analyse and improve personal and group performances in physical activities. Furthermore, it provides students with the opportunity to develop skill sets that enables them to pursue interests in physical activity as athletes, coaches, officials and administrators.

Course Outcomes
Outcome 1: Skills for Physical activity
Outcome 2: Self-management and interpersonal skills for physical activity
Outcome 3: Knowledge and understanding of movement and conditioning concepts for physical activity
Outcome 4: Knowledge and understanding of sport psychology concepts for physical activity

Organisation
The course is designed into a Year 11 syllabus (Units 1 & 2) and a Year 12 syllabus (Units 3 & 4). Each unit is of a semester duration with a notional time of 55 contact hours

Unit 1: Explore anatomical and biomechanical concepts, the body’s responses to physical activity, and stress management processes, to improve the performance of themselves and others in physical activity.

Unit 2: Identify the relationship between skill, strategy and the body in order to improve the effectiveness and efficiency of performance.

Unit 3: Provide opportunities for students to build upon their acquired physical skills and biomechanical, physiological and psychological understandings to improve the performance of themselves and others in physical activity.

Unit 4: Extend the understanding by students of complex biomechanical, psychological and physiological concepts to evaluate their own and others’ performance.

The course content is divided into six interrelated content areas:

- Developing physical skills and tactics
- Motor learning and coaching
- Functional anatomy
- Biomechanics
- Exercise physiology
- Sport psychology

Unit 1 outcomes achieved

Motor learning and coaching

- Types of cues used to improve performance
  - Visual
  - Verbal
  - Proprioreceptive
- Phases of information processing during skill performance
  - Identification of stimuli/input
  - Response identification/decision making
  - Response/output
  - Feedback

Biomechanics

- Definition of linear motion and how it applies to a selected sport in relation to speed, velocity, acceleration, instantaneous measure/mean measure
- Definition of angular motion and how it applies to a selected sport in relation to angular velocity
- Definition of general motion and how it applies to a selected sport

Unit 2 Outcomes achieved

Motor learning and coaching

- Types of feedback
  - intrinsic (inherent)
  - extrinsic (augmented) – terminal, concurrent, verbal, non-verbal
- Purpose of feedback
  - reinforcement
  - motivation
- Relationship between skill learning processes and individual differences related to age, skill and fitness level, injury, level of competition, and type of activity

Functional anatomy

- Movement types created by muscle action and joint movement
  - flexion
  - circumduction
  - extension
  - supination
  - rotation
  - dorsi flexion
  - pronation
  - abduction
  - plantar flexion
  - adduction

Biomechanics

- Definition of Newton's First, Second and Third Laws of Motion, and how they apply to sporting contexts
- The coordination of linear motion
    - sequential versus simultaneous movement – accuracy and power
    - summation of velocity

Unit 3 Outcomes achieved

Motor learning and coaching

- Analyse movement skills of self and others to identify errors, provide feedback and suggest corrections to improve performance
- Design coaching/training activities to improve performance in selected skills, including shaping, chaining, static-dynamic, simple-complex

Biomechanics

- Definition and application of the following concepts in a set sport
    - moment of inertia
    - angular momentum
    - levers
    - three classes of levers
- Application of biomechanical principles to analyse physical skills
    - balance
    - coordination continuum
    - force-motion
    - force-time
    - inertia
    - optimal projection
    - range of motion
    - segmental interaction
    - spin

Unit 4 Outcomes achieved

Motor learning and coaching

- Use checklists and video to analyse and reflect on the performance of themselves and others in physical activity
- Learning and skill development in relation to correction and improvement of self and others
    - use of video analysis
    - reflective journals
    - peer/mentor/coach feedback
    - questionnaires

4.2 Mathematics Methods

General course overview

Mathematics Methods provides a foundation for further studies in disciplines in which mathematics and statistics have important roles. It is also advantageous for further studies in the health and social sciences. In summary, this course is designed for students whose future pathways may involve mathematics and statistics and their applications in a range of disciplines at the tertiary level.

Course Outcomes

- understanding of concepts and techniques drawn from algebra, the study of functions, calculus, probability and statistics
- ability to solve applied problems using concepts and techniques drawn from algebra, functions, calculus, probability and statistics
- reasoning in mathematical and statistical contexts and interpretation of mathematical and statistical information, including ascertaining the reasonableness of solutions to problems
- capacity to communicate in a concise and systematic manner using appropriate mathematical and statistical language
- capacity to choose and use technology appropriately and efficiently.

Organisation

The course is designed into a Year 11 syllabus (Units 1 & 2) and a Year 12 syllabus (Units 3 & 4). Each unit is of a semester duration with a notional time of 55 contact hours

Unit 1: Contains the three topics; Functions and graphs, Trigonometric functions, Counting and Probability.

Unit 2: Contains the three topics; Exponential functions, Arithmetic and geometric sequences and series, Introduction to differential calculus

Unit 3: Contains the three topics; Further differentiation and applications, Integrals, Discrete random variables

Unit 4: Contains the three topics; The logarithmic function, Continuous random variables and the normal distribution, Interval estimates for proportions.

Unit 1 Outcomes achieved

Topic 1.2 Trigonometric functions

- Circular measure and radian measure (Topic 1.2.5 – 1.2.6)

Unit 2 Outcomes achieved

Topic 2.3: Introduction to Differential Calculus

- Rates of change (Topic 2.3.1 – 2.3.4)
- The concept of the derivative (Topic 2.3.5 – 2.3.9)
- Computation of derivatives (Topic 2.3.10 – 2.3.12)
- Properties of derivatives (Topic 2.3.13 – 2.3.15)
- Applications of derivatives (Topic 2.3.16 – 2.3.21)
- Anti-derivatives (Topic 2.3.22)

Unit 3 outcomes achieved

Topic 3.1: Further differentiation and applications

- The second derivative and applications of differentiation (3.1.10 – 3.1.16)

Topic 3.2: Integrals

- Anti-differentiation (Topic 3.2.1)
- Applications of integration (3.2.18 – 3.2.22)

4.3 Mathematics Specialist

General course overview

This course provides opportunities, beyond those presented in the Mathematics Methods ATAR course, to develop rigorous mathematical arguments and proofs, and to use mathematical models more extensively. Mathematics Specialist contains topics in functions and calculus that build on and deepen the ideas presented in the Mathematics Methods course, as well as demonstrate their application in many areas.

Course Outcomes

- understanding of concepts and techniques drawn from combinatorics, geometry, trigonometry, complex numbers, vectors, matrices, calculus and statistics
- ability to solve applied problems using concepts and techniques drawn from combinatorics, geometry, trigonometry, complex numbers, vectors, matrices, calculus and statistics
- capacity to choose and use technology appropriately
- reasoning in mathematical and statistical contexts and interpretation of mathematical and statistical information, including ascertaining the reasonableness of solutions to problems
- capacity to communicate in a concise and systematic manner using appropriate mathematical and statistical language
- ability to construct proofs.

Organisation

The course is designed into a Year 11 syllabus (Units 1 & 2) and a Year 12 syllabus (Units 3 & 4). Each unit is of a semester duration with a notional time of 55 contact hours

Unit 1: Contains the three topics; Combinatorics, Vectors in the plane, Geometry.

Unit 2: Contains the three topics; Trigonometry, Matrices, Real and complex numbers

Unit 3: Contains the three topics; Complex numbers, Functions and sketching graphs, Vectors in three dimensions

Unit 4: Contains the three topics; Integration and applications of integration, Rates of change and differential equations, statistical inference

Unit 1 Outcomes achieved

Topic 1.2 Vectors in the plane

- Representing vectors in the plane by directed line segments (Topic 1.2.1 – 1.2.4)
- Algebra of vectors in the plane (Topic 1.2.5 – 1.2.14)

Unit 2 Outcomes achieved

Topic 2.3: Real and complex numbers

- The complex plane (Topic 2.3.11 – 2.3.13)

Unit 3 Outcomes achieved

Topic 3.1: Complex numbers
- Cartesian forms (Topic 3.1.1 – 3.1.3)
- The complex plane (Topic 3.1.8 – 3.1.10)

Topic 3.3: Vectors in three dimensions
- The algebra of vectors in three dimensions (Topic 3.3.1 – 3.3.2)
- Vector and Cartesian equations (Topic 3.3.3 – 3.3.8)
- Vector calculus (Topic 3.3.11 – 3.3.15)

Unit 4 Outcomes achieved

Topic 4.1: Integration and applications of integration
- Applications of integral calculus (Topic 4.1.5 – 4.1.7)
- The complex plane (Topic 3.1.8 – 3.1.10)

Topic 4.2: Rates of change and differential equations
- Modelling motion (Topic 4.2.7)

4.4 Physics

General course overview
Students have opportunities to develop their investigative skills and use analytical thinking to explain and predict physical phenomena. Students plan and conduct investigations to answer a range of questions, collect and interpret data and observations, and communicate their findings in an appropriate format. Problem-solving and using evidence to make and justify conclusions are transferable skills that are developed in this course.

Contexts that can be investigated in this unit include technologies such as accelerometers, motion detectors, global positioning systems (GPS), energy conversion buoys, music, hearing aids, echo locators, and related areas of science and engineering, such as sports science, car and road safety, acoustic design, noise pollution, seismology, bridge and building design.

Course Outcomes

- investigative skills, including the design and conduct of investigations to explore phenomena and solve problems, the collection and analysis of qualitative and quantitative data, and the interpretation of evidence
- ability to use accurate and precise measurement, valid and reliable evidence, and scepticism and intellectual rigour to evaluate claims
- ability to communicate physics understanding, findings, arguments and conclusions using appropriate representations, modes and genres.

Organisation
The course is designed into a Year 11 syllabus (Units 1 & 2) and a Year 12 syllabus (Units 3 & 4). Each unit is of a semester duration with a notional time of 55 contact hours

Unit 1: Thermal, nuclear and electrical physics

Unit 2: Linear motion and waves

Unit 3: Gravity and electromagnetism

Unit 4: Revolutions in modern physics

Unit 2 Outcomes achieved

Motion and force

Contexts that can be investigated in this unit include technologies such as accelerometers, motion detectors, global positioning systems (GPS), energy conversion buoys, music, hearing aids, echo locators, and related areas of science and engineering, such as sports science, car and road safety, acoustic design, noise pollution, seismology, bridge and building design.

Unit 3 Outcomes achieved

Gravity and Motion
Electromagnetism

Contexts that can be investigated in this unit include technologies, such as artificial satellites, navigation devices, large-scale power generation and distribution, motors and generators, electric cars, synchrotron science, medical imaging, and related areas of science and engineering, such as sports science, amusement parks, ballistics and forensics.

4.5 Engineering Studies

General course overview
The Engineering Studies ATAR course provides opportunities for students to investigate, research and present information through a design process, and then undertake project management to make a functioning product. These activities provide students with opportunities to apply engineering processes, understand underpinning scientific and mathematical principles, develop engineering technology skills and to understand the interrelationships between engineering projects and society.

Course Outcomes
Outcome 1: Engineering process
Outcome 2: Engineering understandings
Outcome 3: Engineering technology skills
Outcome 4: Engineering in society

Organisation
The course is designed into a Year 11 syllabus (Units 1 & 2) and a Year 12 syllabus (Units 3 & 4). Each unit is of a semester duration with a notional time of 55 contact hours

Unit 1: In the development of an engineering project, students study core engineering theory and their chosen specialist area theory. They develop an understanding of different forms of energy, uses of these different forms, and sources of renewable and non-renewable energy.

Unit 2: This unit develops students' understanding of core and specialist area theory to better understand the scientific, mathematical and technical concepts that explain how engineered products function. They study the impact of the different forms of obsolescence in engineering products on society, business and the environment.

Unit 3: In this unit, students develop their understanding of core and specialist area theory. They also study the impacts of obtaining and using the different forms of renewable and non-renewable energy on society, business and the environment.

Unit 4: In this unit, students consider and analyse the stages within the life cycle of engineering products. Students develop and demonstrate an understanding of the impacts on society, business and the environment that occur during the life cycle of engineered products.

Core content
- Engineering design process
- Materials
- Fundamental engineering calculations
- Engineering in society

Outcomes achieved

Specialist engineering fields
Mechanical

- Materials
- Dynamics
- Mechanisms

Newton's Three Laws of Motion in conjunction with equilibrium principles are the basis for analysing engineering mechanisms and motion conversion systems.

OR

Mechatronics

- Laws and principles of electrical/electronics
- Types of motion
- Calculations

An understanding of scientific, mathematical and technical concepts contained in the three content areas coupled with the engineering design process provides students with the opportunity to design, make, analyse, test and evaluate mechatronic devices.

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