Motion Analysis
Research Interest Group

Sports Protocol: Knee Emphasis
Standard Operating Procedures

Contributing Institutions

Children's Hospital Los Angeles

Shriners Hospital Network

Scottish Rite for Children

Children's Hospital of Colorado

Connecticut Children's Medical Center

Nationwide Children's Hospital

Version: 2.2

Last Modified: October 3rd, 2022

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Section I: Working Group Members

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Section II: Background

Understanding the importance of motion analysis for the evaluation of a youth athlete, PRiSM formed the Motion Analysis Research Interest Group (RIG). This group of researchers recognized that lower extremity knee injury should be the initial focus of the RIG as substantial research has been conducted for this patient population and motion analysis standards for evaluating this population would have the greatest immediate clinical impact.

Given this priority, the RIG formed a subcommittee of clinicians and researchers from motion capture labs around the country. The multidisciplinary team of engineers, biomechanists, physical therapists, kinesiologists, and physicians was formed with the intention of developing standards that would be interpretable and clinically useful for all sports medicine professionals. Through dedicated collaboration, working group members developed a standardized ***clinical*** protocol to evaluate patients in rehab for a knee injury. For example, this protocol may serve as a guide for clinical evaluation of patients rehabbing from an anterior cruciate ligament (ACL) injury. The establishment of this standardized protocol has also provided the foundation for future multicenter clinical research using motion capture technology.

This protocol started with procedures developed by the John C. Wilson, Jr. Motion and Sports Analysis Laboratory at Children's Hospital Los Angeles (CHLA). Notably, their protocol was derived from Dr. Chris Powers' research and experience with two-dimensional motion analysis for return-to-sports testing. However, building on the CHLA version of the protocol which incorporated three-dimensional motion analysis techniques, the subcommittee refined and standardized the clinical measurements, marker placement, mathematical / biomechanical model, data collection procedures, performance task details, and data processing procedures through testing and consensus of the contributors listed. Specifically, between January 2020 and July 2022, the subcommittee met regularly to review all aspects of the protocol. Since there was not consensus in the literature or in the current lab procedures across working group members, Scottish Rite for Children conducted substantial testing during the summer of 2020 that supported the selection of specific marker placements and model and task details. Testing included the comparison of two foot, four lower limb, two hip, two pelvis, and twenty-six trunk model variations. Thus, twenty-two subjects were instrumented with fifty markers on the trunk and lower extremities and six marker clusters on the shank and thigh segments and were asked to perform variations of the six tasks outlined in this protocol. More specifically, eight heel touch (or step-down tap), six drop vertical jump, two single leg hop, and two 45° cut variations were tested. Lastly, a scoring rubric will also be added to this protocol after sufficient evaluation and optimization is complete. The drafted scoring criteria under evaluation are derived from a variety of sources including, but not limited to, literature, data from control subjects tested at CHLA, Chris Powers' experience with two-dimensional assessments, and clinical judgement.

To date, the results of this testing has resulted in one publication, four manuscripts in draft, and six presented abstracts, primarily led by Scottish Rite for Children, Shriners Children's Philadelphia, and Children's Hospital Los Angeles. Notably, aspects of this protocol will be updated over time as advancements in motion capture technology and analysis techniques progress.

Section III: Measurements and Marker Placement

III.a Measurements

The following measurements of each participant are either required ([1]) by the provided model described in Section IV or strongly recommended for subsequent data analysis. Measurements that can be calculated using marker positions are denoted with a ([2]).

- Height
- Weight[1] (kg)
- Leg Length[2] (mm) - Distance from the anterior superior iliac spine to the medial malleolus.
- Knee Width[1] (mm) - Distance between the lateral and medial femoral condyles.
    - If the patient has excessive adipose tissue on the medial side, squeeze the calipers together to best measure the bony position of the femoral condyle.
- Ankle Width[1] (mm) - Distance between the lateral and medial malleoli.
    - If the lateral ankle marker is palpated inside the shoe and thus marker placement falls on the shoe, measure the ankle width with the shoe collar included on both sides.
- Sole Delta[1]
    - Use calipers to measure the shoe sole height at the toe marker position and at the center of the heel of the shoe. Subtract the toe sole height from the heel sole height. This value will be used by the model to offset the sagittal plane angle of the foot (details below). The purpose of using Sole Delta is to define foot kinematics as if the foot were flat on the ground during the static as a neutral ankle sagittal angle (0° dorsiflexion).

SD: sole height difference

III.b Marker Adhesion

During athletic tasks, high impact, fast movements, and sweat can lead to issues with markers staying in place. Options to aid with securing markers in place:

- Adhesive Disks – MVAP Medical Supplies Inc.
- Glue – Geritrex Compound Benzoin Tincture or Mastisol Adhesive
- Velcro hook and loop – Feiner Supply
- Tape – Surgical or Transpore tape
- Coban/coflex with double sided tape (for clusters)
- Double sided tape for clusters – Vapon
- Tips:
    - Mark location of skin markers with eyeliner pencil, washable marker, or surgical pen before taping markers down.
    - Use surgical and/or transpore tape to adhere markers to the skin.
    - Use double-sided tape for clusters.
    - Keep the lab slightly cooler to reduce sweating.
    - Shoe markers (two options)
        - Coflex shoe markers to keep them in place.
        - Medical or duct tape has also been used by labs to keep shoe marker on.
    - Remove calibration markers after static.
    - Cover reflective features of shoes or clothing with tape to prevent interference with marker data.

III.c Marker Placement

Tracking markers ® must be present during the static trial to define their position relative to the segment as well as during the dynamic trials to track movement of each segment. Calibration only markers © are required during the static trial but can be removed before dynamic trials. All markers should be placed on the skin, not on clothing, except for foot markers which are placed on the shoe.

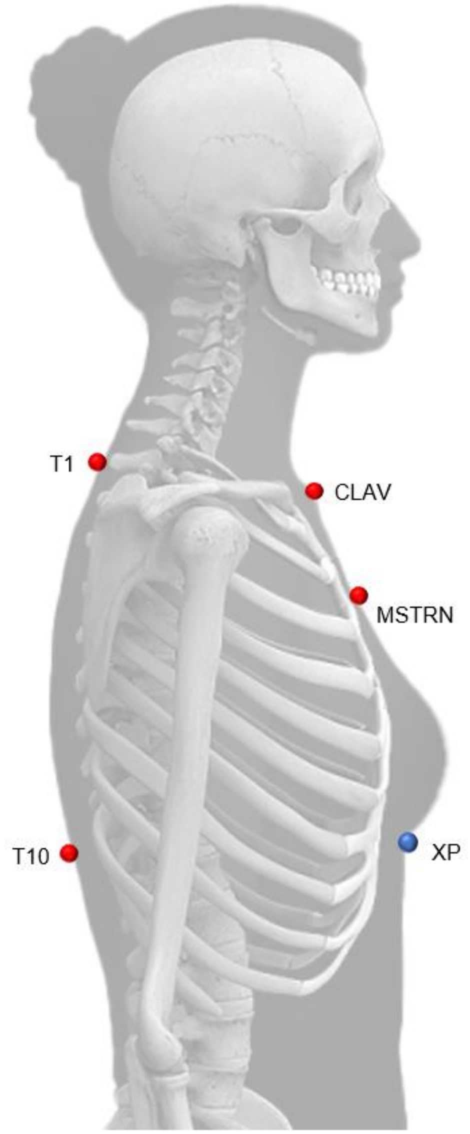
® = tracking, required during both static and dynamic trials
© = calibration, required during static
V = may be defined as virtual marker using dipstick or pointer

Legend
- Tracking Marker
- Calibration Marker
- Gap Filling Marker
- Virtual Marker

NOTE: The shared model/code will allow for alternate marker names to be input if the following names are not used.

Trunk Segment

1. **1st Thoracic Spinous Process – T1** ®
   - Most prominent aspect of T1 spinous process.
   - Find C7 to determine the location of T1. C7 is typically the most prominent spinous process, but occasionally it is C6. To determine between C6 and C7, palpate the spinous process as the patient flexes/extends their neck. C6 will have palpable movement with this motion, while C7 will remain stable. Once identified, count down one spinous process from C7 to identify T1.
2. **10th Thoracic Spinous Process – T10** ®
   - Most prominent aspect of T10 spinous process.
   - Can be moved upward to T9 or T8 if clothing is an obstacle. The marker should not be moved below T10.
3. **Jugular Notch – CLAV** ®
   - Immediately below the jugular notch on the manubrium where the clavicles meet the sternum.
4. **Xiphoid Process – XP** © V
   - May be located by first finding the medial borders of the rib cage and tracing them superiorly until the two borders meet.
   - Can be placed virtually with use of a dipstick due to sports bra location, if needed.
   - Can be removed after the static or left to help with gap filling, whichever is most comfortable for the patient.
5. **Mid-Sternum – MSTRN** ®
   - Midpoint of the sternum between the XP and CLAV markers.
   - Can be placed just superior to sports bra or tank top neckline, if needed.

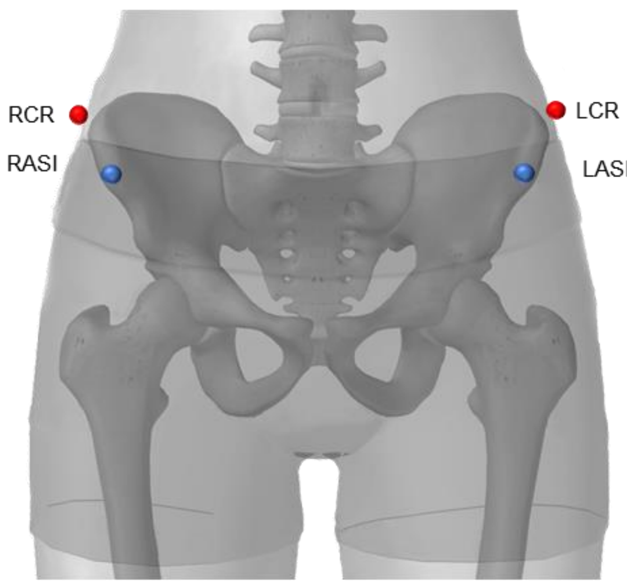


Pelvis Segment

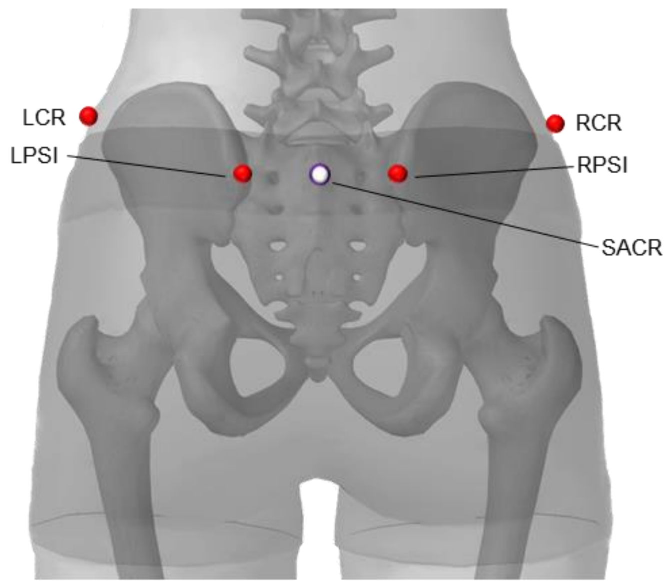
A dipstick can be used to identify the ASIS when its location is occluded or deeply covered by soft tissue. Use of the dipstick should be considered if you anticipate a lot of soft tissue artifact over the ASIS. Alternatively, the dipstick may be used on all patients to determine ASIS location, given that the Iliac Crest markers are used to track the pelvis.

The decision to use two PSIS markers or one sacral marker is at the discretion of the individual labs, with the understanding that the two PSIS markers are used to find the midpoint, which becomes the location of the sacral marker.

1. **Anterior Superior Iliac Spine (ASIS) – LASI, RASI © V**
   - Most anterior point of the ASIS. Place hands on the side of the patient's trunk and palpate iliac crest with thumbs. Move downward until you reach the ilium. Trace your thumbs anteriorly until you identify the first bony prominence. Verification of marker placement may also be done by palpating from below the ASIS.
   - ASIS markers can be left on after the static trial to be used for gap filling purposes, if needed.
2. **Iliac Crest – LCR, RCR ®**
   - Most prominent point at the top of the iliac crest that falls along the anterior-posterior midline.
3. **Posterior Superior Iliac Spine (PSIS) – LPSI, RPSI ® *or Sacrum (SACR)**
   - Start with hands located at the top of the iliac crest and use thumbs to locate the PSIS. Place markers at the most prominent point of each PSIS. Having two PSIS markers helps with drop out compared to a single sacral marker.
   - If using a sacral marker, it should be placed at the midpoint between the PSIS. If a SACR marker is not used, its location will be computed using the two PSIS markers.



Anterior



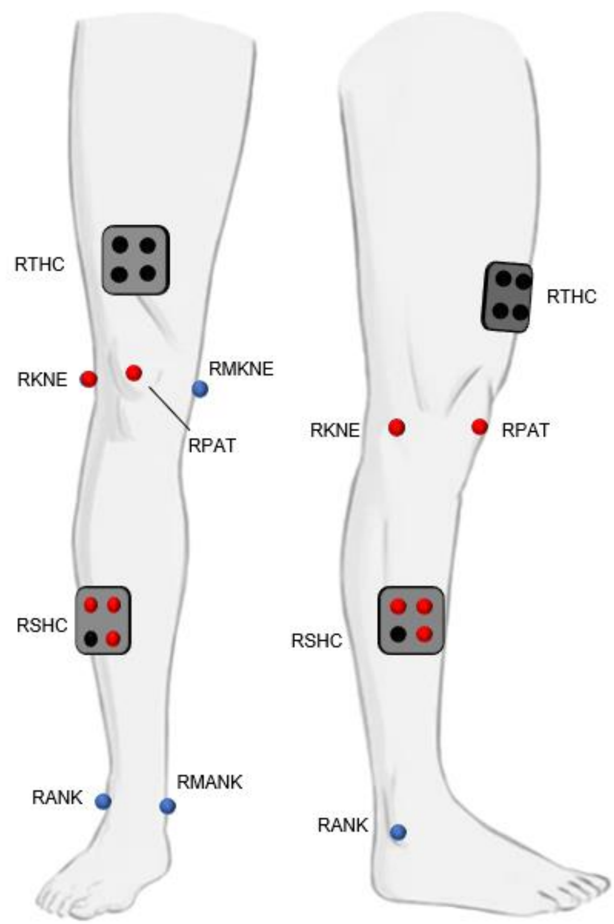
Posterior

Thigh Segment

The lower extremity model will be defined using a combination of three and six degrees-of-freedom (DoF) modeled joints. Although a 6DoF model is commonly used in sports testing, the working group found concerning inconsistency in knee coronal motion primarily due to excessive hip motion. Therefore, in the provided model, the hip joint is constrained using a 3DoF model while knee and ankle joint motion is defined using a 6DoF model (hybrid LE model). Thus, the thigh segment will be tracked using the lateral knee marker (LKNE), patella marker (PAT), and hip joint center (HJC).

If an individual lab would prefer to model the lower extremities with a 6DoF model rather than the hybrid LE model, a thigh cluster (THC) placed anteriorly on the distal third of the thigh is recommended. Details for this alternative are described below.

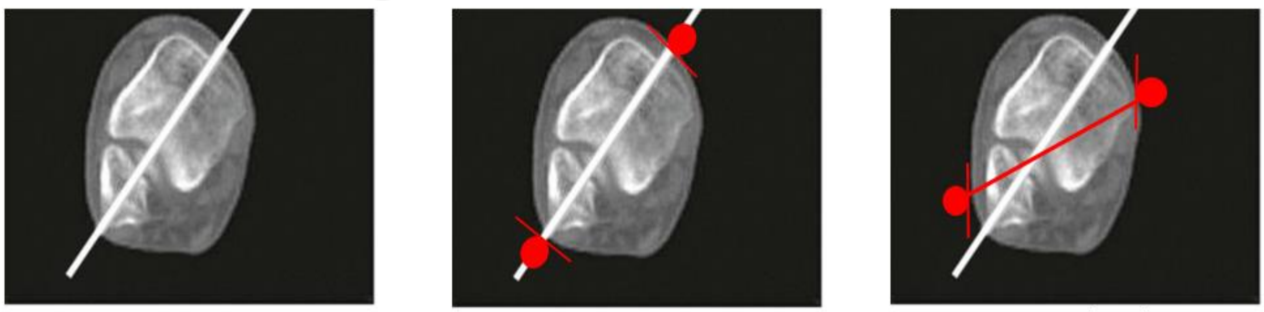
1. **Lateral Femoral Condyle (LKNE, RKNE)** Ⓡ
   - In line with knee flexion/extension axis**,** palpate the lateral knee joint for the boniest prominence. Having the patient flex/extend their knee during standing or pose in a small squat position may help locate this placement. It is important to note that the most lateral prominence may not necessarily be on the flexion/extension axis. Thus, placement may need to be adjusted accordingly to place the marker in line with this axis.
   - This marker is used in combination with the medial femoral condyle marker (MKNE) to define the knee flexion/extension axis.
2. **Medial Femoral Condyle (LMKNE, RMKNE)** Ⓒ
   - In line with knee flexion/extension axis, palpate the medial knee joint for the boniest prominence. Having the patient flex/extend their knee during standing may help locate this point. Placement may be adjusted to align the marker with the flexion/extension axis.
3. **Patella (LPAT, RPAT)** Ⓡ
   - Center of the most anterior point on the patella. Marker placement is easiest when the patient is standing to avoid placing the marker too low.
4. ***Alternative:* Thigh Cluster Plate (LTHC1-4, RTHC1-4)** Ⓡ
   - Markers pre-attached to a molded thermoplastic plate (example: B&L engineering). Use double-sided tape on the back of the plates to secure them onto each thigh. The clusters should be placed on the anterior distal third of the thigh.
   - Cluster plates may include three or four markers. These markers may be used as a second alternative option for tracking the thigh segment.
   - *If using this alternative method, the KNE and MKNE markers are still required in the static trial to compute the knee joint center, but the PAT marker is no longer required, although it could remain on for compatibility with multicenter studies.*



<u>Shank Segment</u>

1. **Tibial Cluster Plate (LSHC1-4, RSHC1-4)** ®
   - The proximal medial marker of the cluster is placed along the anterior crest of the tibia at the midpoint between the ANK and KNE markers, with the majority of the cluster positioned lateral to the crest. As the cluster is used for tracking purposes only, the exact position on the tibia is not critical.
   - Cluster plates may include three or four markers. Only three markers will be used for tracking, however, the fourth marker may be helpful for gap filling.
2. **Lateral Malleolus (LANK, RANK)** ©
   - Center of the lateral malleolus, not necessarily the most prominent point.
3. **Medial Malleolus (LMANK, RMANK)** ©
   - Center of the medial malleolus, not necessarily the most prominent point.
   - Used in combination with the lateral malleolus marker (ANK) to define the ankle dorsiflexion/plantarflexion axis. See ankle axis alignment figure below.

Ankle axis alignment



Ankle Axis – defined by line from the midpoint of each malleolus

Correct marker placement
In plane of axis

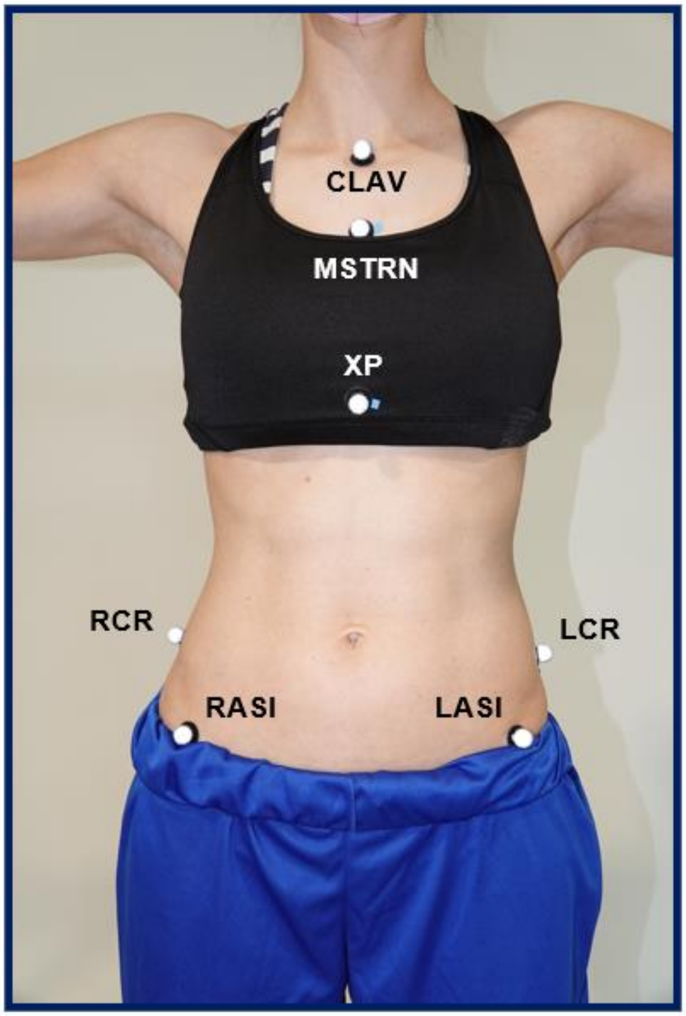
Incorrect marker placement
Most prominent, but not in plane of axis

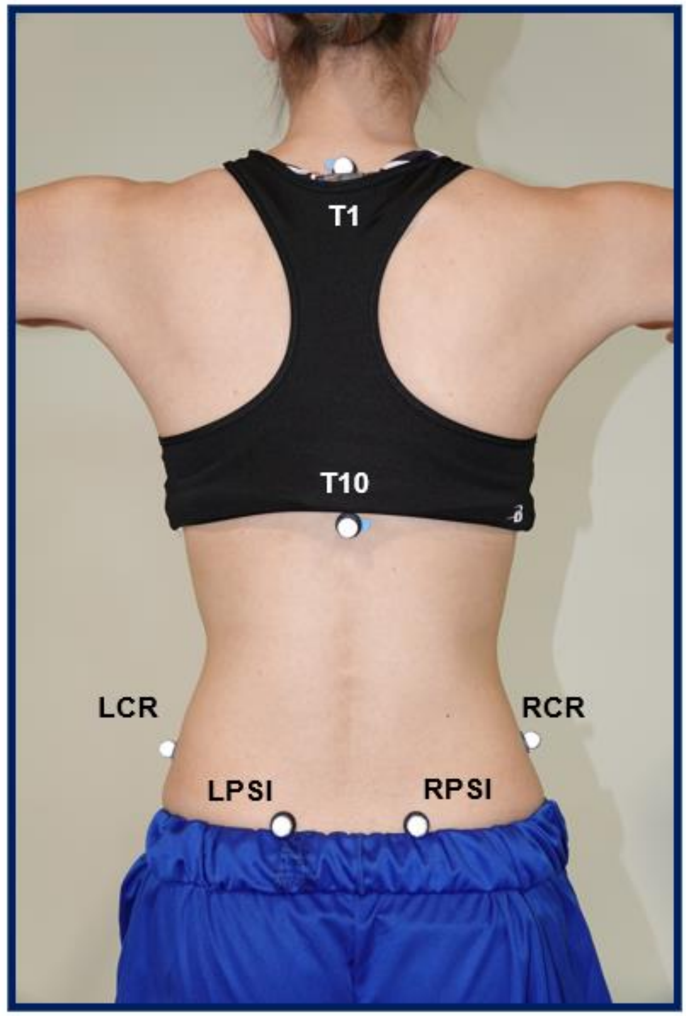
Foot Segment

1. **Between 2nd/3rd Metatarsal Heads (LTOE, RTOE) ®**
   - Best approximation between the 2nd and 3rd metatarsal heads when palpating through the patient's shoe. Move marker more proximal if needed to avoid excessive motion from the toe box. May need to flex toes/shoe to approximate position.
2. **5th Metatarsal Head (LMET, RMET) ®**
   - Best approximation of the location of the 5th metatarsal head when palpating through the patient's shoe. Place laterally, immediately above the sole. Move marker more proximal if needed to avoid excessive motion from the toe box. May need to flex toes/shoe to approximate position.
3. **Hindfoot Midline (LHEE, RHEE) ®**
   - Midline of the hindfoot above the sole of the shoe. It is important to avoid placing the marker on the sole of the shoe or any part of the shoe that will morph during high impact. Thus, placement may vary in height relative to the toe marker. It is okay if the height of the toe and heel markers are not the same as the model will mathematically adjust the height of these markers.

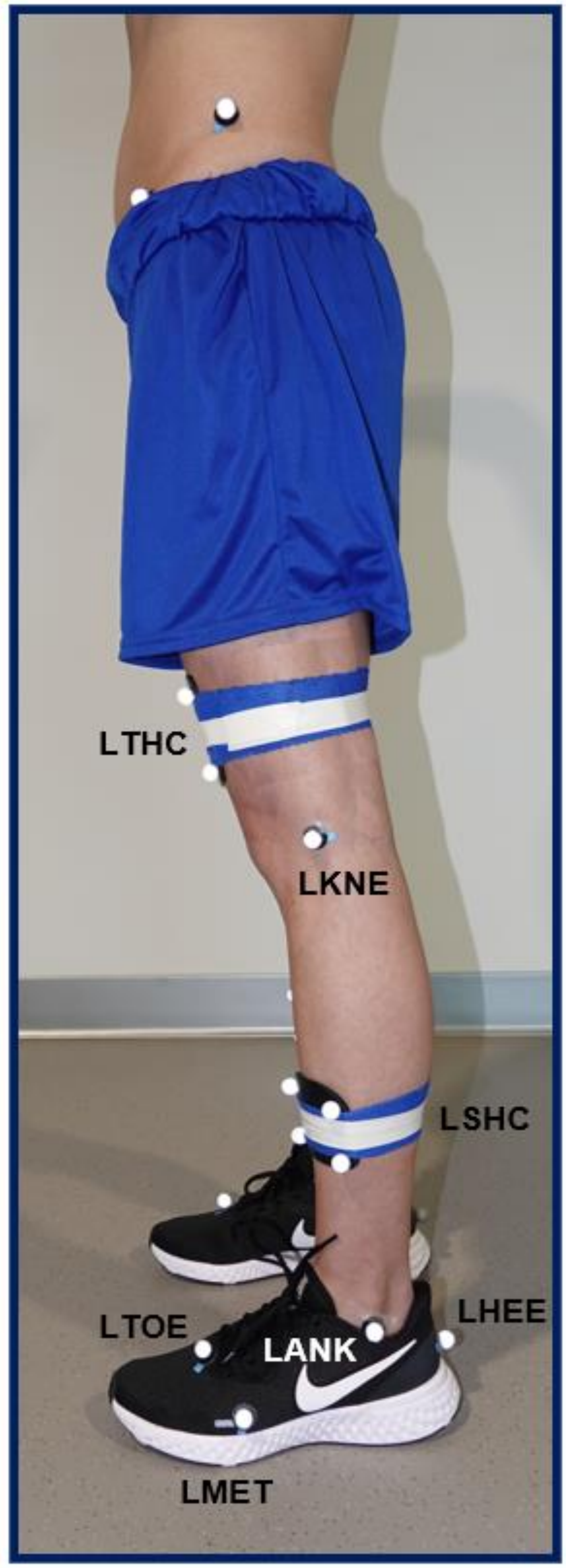
Marker Placement Example: Trunk and Pelvis Segments

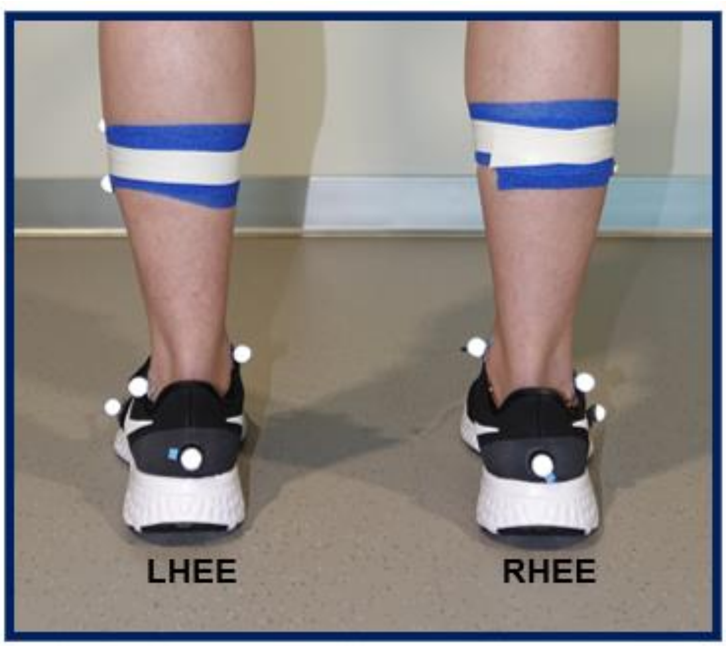
In this example, a dipstick should be used to identify the accurate location of the XP marker. During marker placement, the XP location was palpated and identified as being located under the sports bra. However, given that the gap between the fabric and the true XP location will cause the marker placement and thus trunk centerline to be shifted anteriorly, a dipstick should be used. (A marker was only placed on the sports bra for the purpose of representing the XP location in this picture.)





Marker Placement Example: Lower Extremity Segments



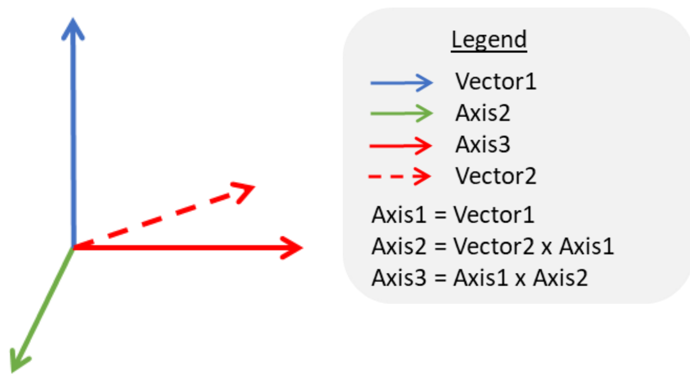


Section IV: Model

In the static trial, virtual markers of the trunk and pelvis and joint centers of the hip, knee, and ankle are calculated (IV.a), and technical/tracking coordinate systems are defined using surface markers. Similarly, anatomical coordinate systems are created using joint centers and markers to represent each body segment (IV.b). To calculate each coordinate system, two vectors are defined: Vector1 and Vector2. First, the primary axis (Axis1) of each segment is set equal to Vector1. Then, the cross product is taken of Vector2 and Axis1 (Vector2 x Axis1). This will define a new axis (Axis2) which is orthogonal to Axis1 and Vector2. Finally, the cross product is taken of Axis1 and Axis2 to create the third axis (Axis 3) of the coordinate system (see figure below). It is important to note that for each body segment definition, Vector1 could be the sagittal axis, coronal axis, or the transverse axis depending on which axis is the primary axis of the respective body segment. Therefore, the primary axis of each coordinate system is strategically chosen and defined as Vector1. For every coordinate system defined in this model, the positive direction of the sagittal axis points to the right of the segment, the coronal axis points forward, and the transverse axis points up when the subject is standing in the anatomical position.

In Section IV.b, the definition of the sagittal, coronal, and transverse axes of each body segment are explained. For example, for the pelvis anatomical coordinate system, the sagittal axis (SagAxis) is defined as Vector 1 (the vector from the left anterior superior iliac spine to the right anterior superior iliac spine). The transverse axis (TransAxis) is then defined as the cross-product of Vector2 (the vector from the midpoint of the anterior superior iliac spines to the sacrum) and SagAxis. Finally, the coronal axis (CorAxis) is defined as the cross-product of TransAxis and SagAxis.

After each segment coordinate system is created, transformation matrices are calculated for each anatomical coordinate system relative to that body segment's technical coordinate system using the specified rotation sequence. In the static trial, these transformation matrices are computed, averaged across the length of the trial, and saved. In the dynamic trials, the technical coordinate systems are created and transformed using the saved transformation matrices to estimate the anatomical coordinate systems. Finally, Euler angles between the child and parent segment anatomical coordinate systems are calculated to determine the joint angles using the rotation sequences in Section IV.c.



IV.a Virtual Markers, Joint Centers, and Offsets

1. **Trunk Segment**
   - Superior Trunk (TSUP) – Midpoint of T1 and CLAV markers.
   - Inferior Trunk (TINF) – Midpoint of T10 and XP markers.
   - Inferior Trunk 2 (TINF2) – Midpoint of T10 and MSTRN markers.
   - Anterior Trunk (TANT) – Midpoint of CLAV and XP markers.
   - Anterior Trunk 2 (TANT2) – Midpoint of CLAV and MSTRN markers.
   - Posterior Trunk (TPOS) – Midpoint of T1 and T10 markers.

2. **Pelvis Segment**
   - Sacrum (SACR) – Midpoint of RPSI and LPSI markers. *Calculated only if SACR marker is not present.*
   - Mid-Anterior Superior Iliac Spine (MASI) – Midpoint of LASI and RASI markers.
   - Mid-Iliac Crest (MCR) – Midpoint of LCR and RCR markers.

3. **Hip Joint Center (LHJC, RHJC)**
   - Calculated according to Harrington et al. [1], specifically equations 5-7.
     i. Hip joint center offsets (in mm) from the MASI position are as follows:
        - Sagittal = 0.33 * (pelvis width) + 7.3
        - Coronal = -0.24 * (pelvis depth) – 9.9
        - Transverse = -0.30 * (pelvis width) – 10.9
   - Pelvis depth is the distance between the MASI and the SACR.
   - Pelvis width is the distance between the two ASIS markers.

4. **Knee Joint Center (LKJC, RKJC)**
   - The lateral knee marker position moved ½ of the measured knee width plus the marker radius medially along the sagittal axis of the thigh coordinate system.

5. **Ankle Joint Center (LAJC, RAJC)**
   - The lateral ankle marker position moved ½ of the measured ankle width plus the marker radius medially along the sagittal axis of the shank coordinate system.

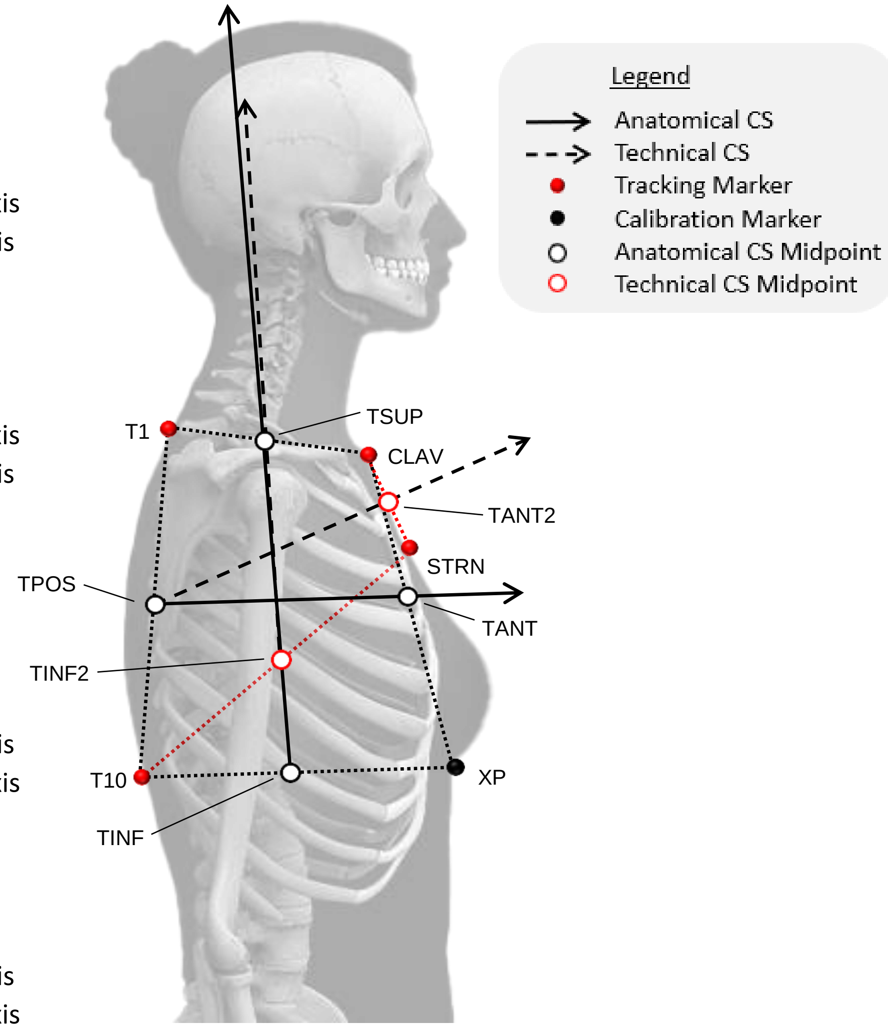
6. **Adjusted TOE Position ($LTOE_{adjusted}$, $RTOE_{adjusted}$)**
   - Vertical position of the TOE is set equal to the height of the AJC and decreased by the sole delta value.

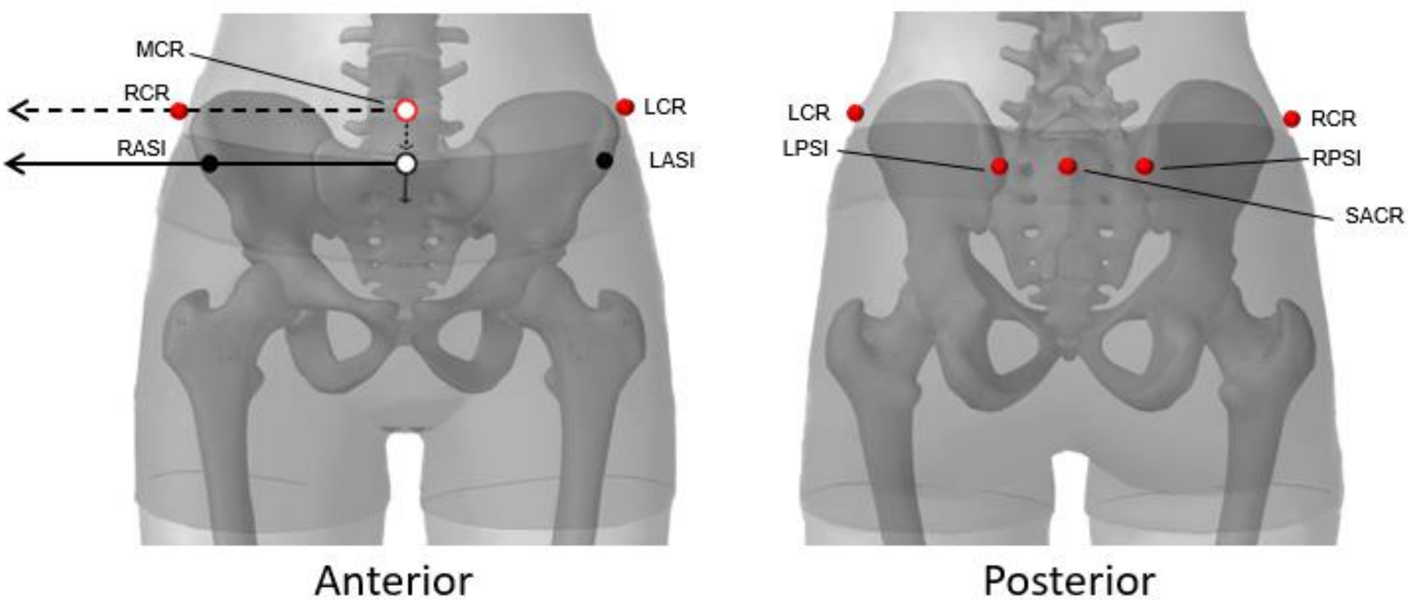
7. **Adjusted 5th Metatarsal Position ($LMET_{adjusted}$, $RMET_{adjusted}$)**
   - Vertical position of the MET is set equal to the height of the AJC and decreased by the sole delta value.

[1] M.E. Harrington, A.B. Zavatsky, S.E. Lawson, Z. Yuan, T.N. Theologis, Prediction of the hip joint centre in adults, children, and patients with cerebral palsy based on magnetic resonance imaging, J Biomech 40 (2007) 595-602.

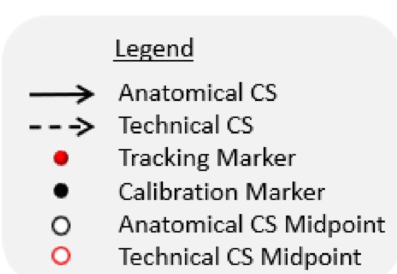
IV.b Coordinate System Definitions

1. **Trunk Segment**
   - *Technical Coordinate System*
     i. Vector1 = TINF2 to TSUP
     ii. Vector2 = TPOS to TANT2
     iii. **SagAxis** = Vector2 x TransAxis
     iv. **CorAxis** = TransAxis x SagAxis
     v. **TransAxis** = Vector1
   - *Anatomical Coordinate System*
     i. Vector1 = TINF to TSUP
     ii. Vector2 = TPOS to TANT
     iii. **SagAxis** = Vector2 x TransAxis
     iv. **CorAxis** = TransAxis x SagAxis
     v. **TransAxis** = Vector1
2. **Pelvis Segment**
   - *Technical Coordinate System*
     i. Vector1 = LCR to RCR
     ii. Vector2 = MCR to SACR
     iii. **SagAxis** = Vector1
     iv. **CorAxis** = TransAxis x SagAxis
     v. **TransAxis** = Vector2 x SagAxis
   - *Anatomical Coordinate System*
     i. Vector1 = LASI to RASI
     ii. Vector2 = MASI to SACR
     iii. **SagAxis** = Vector1
     iv. **CorAxis** = TransAxis x SagAxis
     v. **TransAxis** = Vector2 x SagAxis

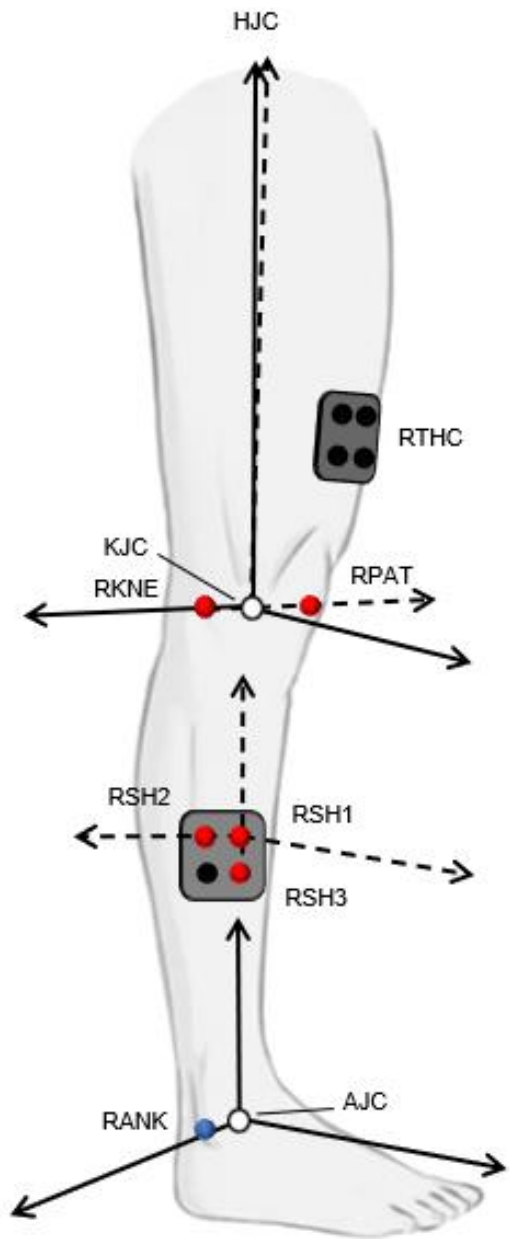




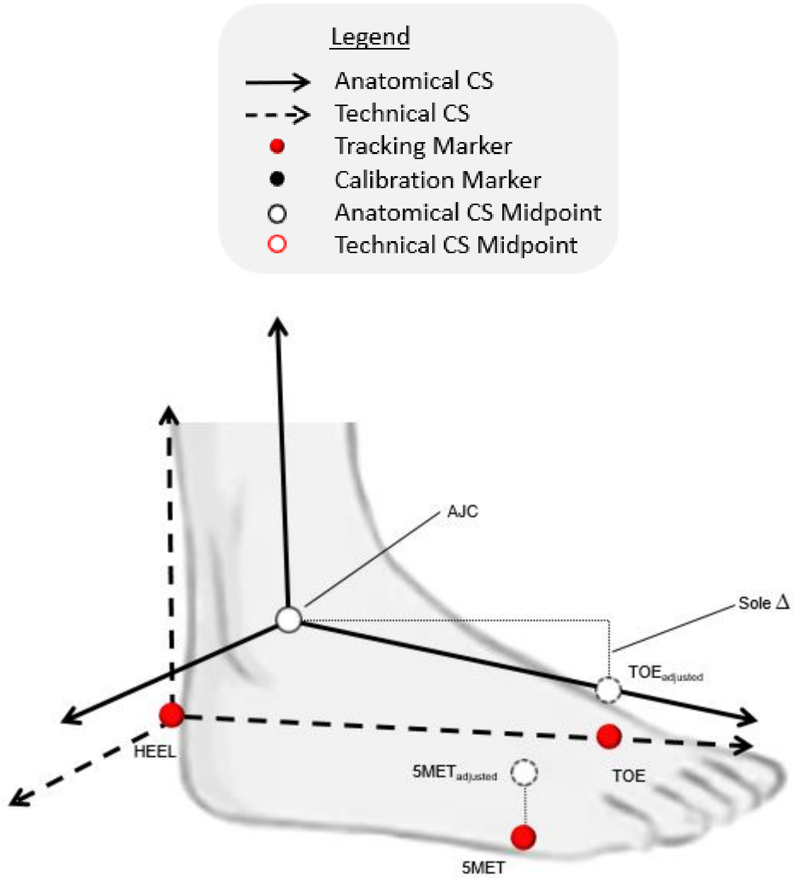
3. **Left Thigh Segment**
   - *Technical Coordinate System*
     i. Vector1 = LKNE to LHJC
     ii. Vector2 = LKNE to LPAT
     iii. **SagAxis** = Vector2 x TransAxis
     iv. **CorAxis** = TransAxis x SagAxis
     v. **TransAxis** = Vector1
   - *Anatomical Coordinate System*
     i. Vector1 = LKJC to LHJC
     ii. Vector2 = LMKN to LKNE
     iii. **SagAxis** = CorAxis x TransAxis
     iv. **CorAxis** = Vector2 x TransAxis
     v. **TransAxis** = Vector1
4. **Right Thigh Segment**
   - *Technical Coordinate System*
     i. Vector1 = RKNE to RHJC
     ii. Vector2 = RKNE to RPAT
     iii. **SagAxis** = Vector2 x TransAxis
     iv. **CorAxis** = TransAxis x SagAxis
     v. **TransAxis** = Vector1
   - *Anatomical Coordinate System*
     i. Vector1 = RKJC to RHJC
     ii. Vector2 = RKNE to RMKN
     iii. **SagAxis** = CorAxis x TransAxis
     iv. **CorAxis** = Vector2 x TransAxis
     v. **TransAxis** = Vector1
5. **Left Shank Segment**
   - *Technical Coordinate System*
     i. Vector1 = LSH2 to LSH1
     ii. Vector2 = LSH3 to LSH1
     iii. **SagAxis** = Vector1
     iv. **CorAxis** = Vector2 x SagAxis
     v. **TransAxis** = SagAxis x CorAxis
   - *Anatomical Coordinate System*
     i. Vector1 = LAJC to LKJC
     ii. Vector2 = LMANK to LANK
     iii. **SagAxis** = CorAxis x TransAxis
     iv. **CorAxis** = Vector2 x TransAxis
     v. **TransAxis** = Vector1



6. **Right Shank Segment**
   - *Technical Coordinate System*
     i. Vector1 = RSH1 to RSH2
     ii. Vector2 = RSH3 to RSH1
     iii. **SagAxis** = Vector1
     iv. **CorAxis** = Vector2 x SagAxis
     v. **TransAxis** = SagAxis x CorAxis
   - *Anatomical Coordinate System*
     i. Vector1 = RAJC to RKJC
     ii. Vector2 = RANK to RMANK
     iii. **SagAxis** = CorAxis x TransAxis
     iv. **CorAxis** = Vector2 x TransAxis
     v. **TransAxis** = Vector1



7. **Left Foot Segment**
   - *Technical Coordinate System*
     i. Vector1 = LHEE to LTOE
     ii. Vector2 = LMET to LHEE
     iii. **SagAxis** = CorAxis x TransAxis
     iv. **CorAxis** = Vector1
     v. **TransAxis** = Vector2 x CorAxis
   - *Anatomical Coordinate System*
     i. Vector1 = LAJC to $\text{LTOE}_{\text{adjusted}}$
     ii. Vector2 = $\text{LMET}_{\text{adjusted}}$ to LAJC
     iii. **SagAxis** = CorAxis x TransAxis
     iv. **CorAxis** = Vector1
     v. **TransAxis** = Vector2 x CorAxis
8. **Right Foot Segment**
   - *Technical Coordinate System*
     i. Vector1 = RHEE to RTOE
     ii. Vector2 = RHEE to RMET
     iii. **SagAxis** = CorAxis x TransAxis
     iv. **CorAxis** = Vector1
     v. **TransAxis** = Vector2 x CorAxis
   - *Anatomical Coordinate System*
     i. Vector1 = RAJC to $\text{RTOE}_{\text{adjusted}}$
     ii. Vector2 = RAJC to $\text{RMET}_{\text{adjusted}}$
     iii. **SagAxis** = CorAxis x TransAxis
     iv. **CorAxis** = Vector1
     v. **TransAxis** = Vector2 x CorAxis



Segment	Vector1	Vector2	Sagittal Axis	Coronal Axis	Transverse Axis
Trunk - T	TINF2 to TSUP	TPOS to TANT2	Vector2 x TransAxis	TransAxis x SagAxis	Vector1
Trunk - A	TINF to TSUP	TPOS to TANT	Vector2 x TransAxis	TransAxis x SagAxis	Vector1
Pelvis - T	LCR to RCR	MCR to SACR	Vector1	TransAxis x SagAxis	Vector2 x SagAxis
Pelvis - A	LASI to RASI	MASI to SACR	Vector1	TransAxis x SagAxis	Vector2 x SagAxis
Left Thigh - T	LKNE to LHJC	LKNE to LPAT	Vector2 x TransAxis	TransAxis x SagAxis	Vector1
Left Thigh - A	LKJC to LHJC	LMKN to LKNE	CorAxis x TransAxis	Vector2 x TransAxis	Vector1
Right Thigh - T	RKNE to RHJC	RKNE to RPAT	Vector2 x TransAxis	TransAxis x SagAxis	Vector1
Right Thigh - A	RKJC to RHJC	RKNE to RMKN	CorAxis x TransAxis	Vector2 x TransAxis	Vector1
Left Shank - T	LSH2 to LSH1	LSH3 to LSH1	Vector1	Vector2 x SagAxis	SagAxis x CorAxis
Left Shank - A	LAJC to LKJC	LMANK to LANK	CorAxis x TransAxis	Vector2 x TransAxis	Vector1
Right Shank - T	RSH1 to RSH2	RSH3 to RSH1	Vector1	Vector2 x SagAxis	SagAxis x CorAxis
Right Shank - A	RAJC to RKJC	RANK to RMANK	CorAxis x TransAxis	Vector2 x TransAxis	Vector1
Left Foot - T	LHEE to LTOE	LMET to LHEE	CorAxis x TransAxis	Vector1	Vector2 x CorAxis
Left Foot - A	LACJ to $\text{LTOE}_{\text{adjusted}}$	$\text{LMET}_{\text{adjusted}}$ to LAJC	CorAxis x TransAxis	Vector1	Vector2 x CorAxis
Right Foot - T	RHEE to RTOE	RHEE to RMET	CorAxis x TransAxis	Vector1	Vector2 x CorAxis
Right Foot - A	RAJC to $\text{RTOE}_{\text{adjusted}}$	RAJC to $\text{RMET}_{\text{adjusted}}$	CorAxis x TransAxis	Vector1	Vector2 x CorAxis

*The technical and anatomical coordinate systems of each segment are denoted by a “T” and “A” in the Segment column, respectively.

IV.c Kinematic Calculations

Angle	Parent Segment	Child Segment	Rotation Sequence
Trunk	Global	Trunk	Transverse/Coronal/Sagittal
Pelvis	Global	Pelvis	Transverse/Coronal/Sagittal
Hip	Pelvis	Thigh	Sagittal/Coronal/Transverse
Knee	Thigh	Shank	Sagittal/Coronal/Transverse
Ankle	Shank	Foot	Sagittal/Coronal/Transverse
Foot	Global	Foot	Sagittal/Coronal/Transverse

*For the hip, knee, and ankle, positive angles represent flexion, adduction, and internal rotation. Positive angles of the trunk represent anterior flexion, trunk lean towards the contralateral side, and internal rotation. Positive angles of the pelvis represent anterior tilt, elevated obliquity, and internal rotation. To maintain that positive or negative values of the left/right side coronal and transverse angles demonstrate the same movements on both sides, various angles are inverted on one side of the body. At the pelvis and trunk, right coronal and left transverse angles are inverted. For the hip, knee, and ankle, left coronal and transverse angles are inverted.

IV.d Kinetic Calculations

Anthropometric relationships are from Dempster et al. as reported in *Biomechanics and Motor Control of Human Movement* [2]. Each segment center-of-mass is computed assuming each segment exhibits the shape of a cone, similar to the method used in Visual3D (described on the C-Motion website here).

[2] D. A. Winter. *Biomechanics and Motor Control of Human Movement.* 4th ed., Wiley, 2009, pp. 86.

Section V: Data Collection

<u>Collection Rates</u>

1. ***Motion Capture Cameras:*** minimum of 240 Hz
2. ***Force Plates:*** minimum of 960 Hz

For each task listed below, there are notes for the task, patient and equipment setup, instructions, and what to look for during performance of the task. **Please read thoroughly before testing.**

Briefly, two of the six tasks are considered 'core tasks' and the remaining four tasks have been identified as 'optional tasks.' **However, it is important to note that outcome variables from all six tasks will be needed in the scoring rubric.**

Overview of Testing:

a. Static standing trial
b. Quality check using walking trial
c. Warmup (Treadmill running; optional)
d. Drop vertical jump – *core task*
e. 45° cut – *core task*
f. Single leg hop – *optional task*
g. Deceleration – *optional task*
h. Heel touch – *optional task*
i. Lateral shuffle – *optional task*
j. Isokinetic strength testing (optional)

Tips: Order of tasks (d – j) is up to the discretion of the lab, however, consider the following:

- Order tasks such that the patient alternates between running (cut, deceleration, shuffle) and non-running tasks.
- Order tasks by difficulty such that apprehension from the patient for a certain level of difficulty does not disrupt the remaining tasks.
- Order tasks by importance such that core tasks are collected regardless of early termination of testing
    - Example order – heel touch, 45° cut, drop vertical jump, lateral shuffle, single leg hop, deceleration

V.a Static Standing Trial

1. ***Notes:***
    a. A standardized position should be used consistently (Ex: T-pose).
    b. Data should be collected for approximately 1-3 secs.
2. ***Patient set up:***
    a. Static markers required per standard protocol and/or additional markers (see previous sections).
    b. Feet: hip width apart, pointing forward, feet plantigrade.
    c. Trunk upright.
    d. Arms out to side at shoulder height, hands facing down with elbows straight (T-pose).
    e. Looking straight ahead.
3. ***Patient Instructions:***
    a. "First we are going to collect a trial of you standing in the middle. Place your feet hip width apart, facing straight ahead. I would like you to hold your arms out to the side, hands facing down at the level of your shoulders, and look straight ahead. Please hold this position for a second or two, until I tell you to relax."
    b. Demonstrate the standardized static position to the subject.
4. ***Performance:***
    a. Check that they maintain the T-pose for the duration of the trial with minimal movement.

V.b Quality check using walking trial

Collect a single walking trial with a minimum of three strides per leg.

- Process a full gait cycle for each leg and visually inspect kinematic graphs to confirm marker placement. For example, identify possible crosstalk affecting the knee varus/valgus graph during swing phase.
- *Currently developing a systematic approach for identifying necessary marker placement adjustments.*

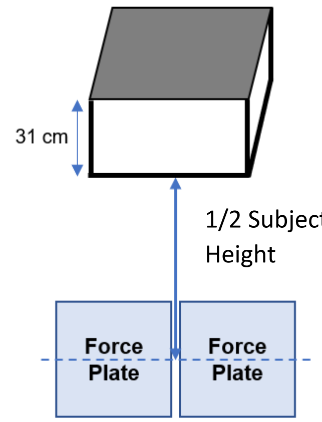
V.c Warmup (Treadmill running; optional)

1. ***Notes:***
   a. Running at self-selected pace.
   b. Performed with appropriate running shoes.
   c. Make sure patient is safe to run on a treadmill based on previous experience, injuries, age, etc.
2. ***Patient Instructions:***
   a. "You will be running for a few minutes on the treadmill. You will warm up for 1-3 minutes at a jogging pace. You can then gradually increase your speed until you feel your running pace is set. You should choose a running pace that is fast but that you could sustain. You will run at this pace for approximately one minute. You can then walk for 30-60 seconds for a cool down."
3. ***Performance:***
   a. 1-3 minute warm up at self-selected jogging pace.
   b. Patient increases speed until running at self-selected pace.
   c. After sufficient warm-up, cue patient to begin a 30-60 second walking cool down.
4. ***Modification:***
   a. Patient may also warm-up on an exercise bike, if needed.
   b. Recommended bike protocol: ~5 minutes with slight resistance.

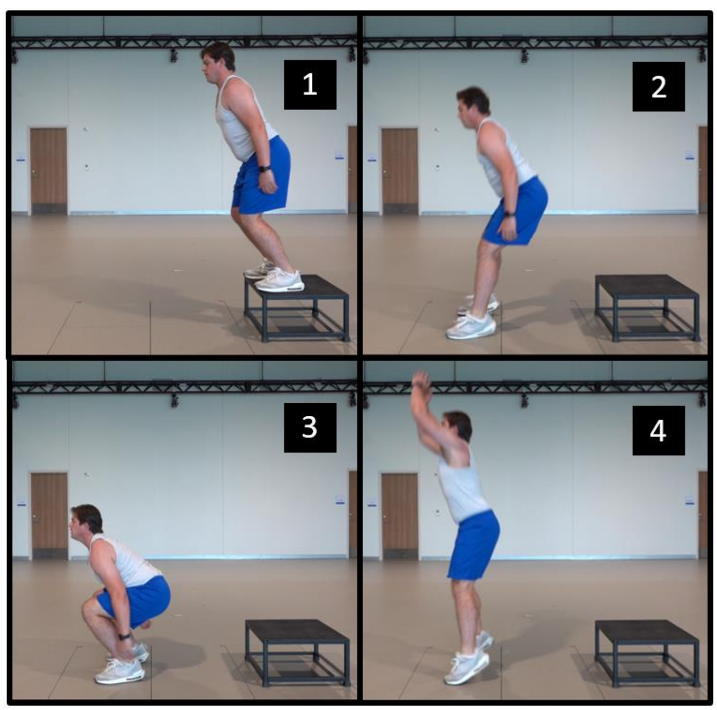
<u>Sports Tasks</u>: Six sports tasks have been described in detail below. Two of the six tasks are considered 'core tasks' and therefore, should be collected if the patient is able. The remaining four tasks have been identified as 'optional tasks' and may follow the outlined procedures or one of the variations listed in the Optional Task Variations section of the Appendix. **However, it is important to note that outcome variables from all six tasks will be needed for scoring purposes once the scoring rubric is released.**

For the following six sports tasks, the patient will be instructed on how to complete the task, they will watch a video that demonstrates the task, and they will then practice until comfortable before performing the task for data collection. All tasks should be performed in appropriate athletic attire and athletic shoe wear.
Demonstration videos for each task will be available soon.

V.d Drop Vertical Jump – *core task*

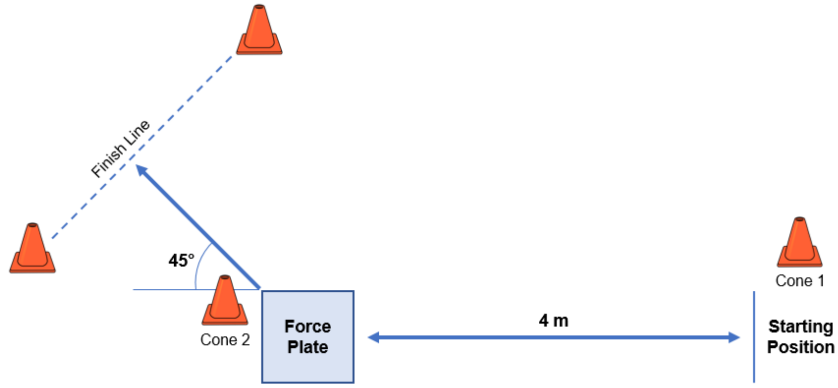


1. ***Set up:***
   a. Place a 12-inch (31 cm) box behind two force plates at a distance one-half of the patient's height from the front of the box to the center of the force plates and centered such that the patient may land with one foot on each plate.
   b. Make sure the box will not tip over (i.e., place a weight on top if unstable).
   c. Position video cameras for front and lateral views.
   d. Patient begins standing on the box however they would like, facing forward.
2. ***Instructions:***
   a. "Jump off of both feet from the box. Hop forward (not up) and land with one foot in each square. Then, immediately jump up as high as you can and land back down with one foot in each square. Complete the entire task in one fluid motion"
      i. Cues:
         - Feel free to use your arms for momentum.
         - Both feet should come off the box at the same time.
         - Try to land with both feet hitting the ground at the same time.
         - Jump as high as you can only after the first landing.
   b. A trial is disqualified if the patient does not land in the force plates on the initial landing.
      i. Collect 3 good trials.
      ii. Allow 2-3 practice trials as needed.
3. ***Performance:***
   a. Both feet should take-off and land at the same time, during initial landing and second landing.
   b. One foot should land in each box (force plate), during initial landing.
      i. Force plate strikes in the second landing are optional and up to the lab's discretion as this may increase the number of attempts required to obtain good trials.
      ii. Regardless, the jump between initial and second landings should be as vertical as possible.
   c. One fluid motion throughout the entire task
4. ***Modification:***
   a. If the half-height distance is too challenging for the patient, a drop jump will be collected instead.
      i. *Set up:* Place the box directly behind the two force plates.



V.e 45° Cut – *core task*

1. ***Set up:***
   a. The run-up area should be as long as the lab space allows, or approximately 10-15 feet long.
   b. Cones should be placed at the starting position, immediately behind the force plate offset from center, and at a 45˚ angle approximately 1m away from the force plate to create a finish line.
   c. The patient will start at the beginning of the "runway" facing forward.

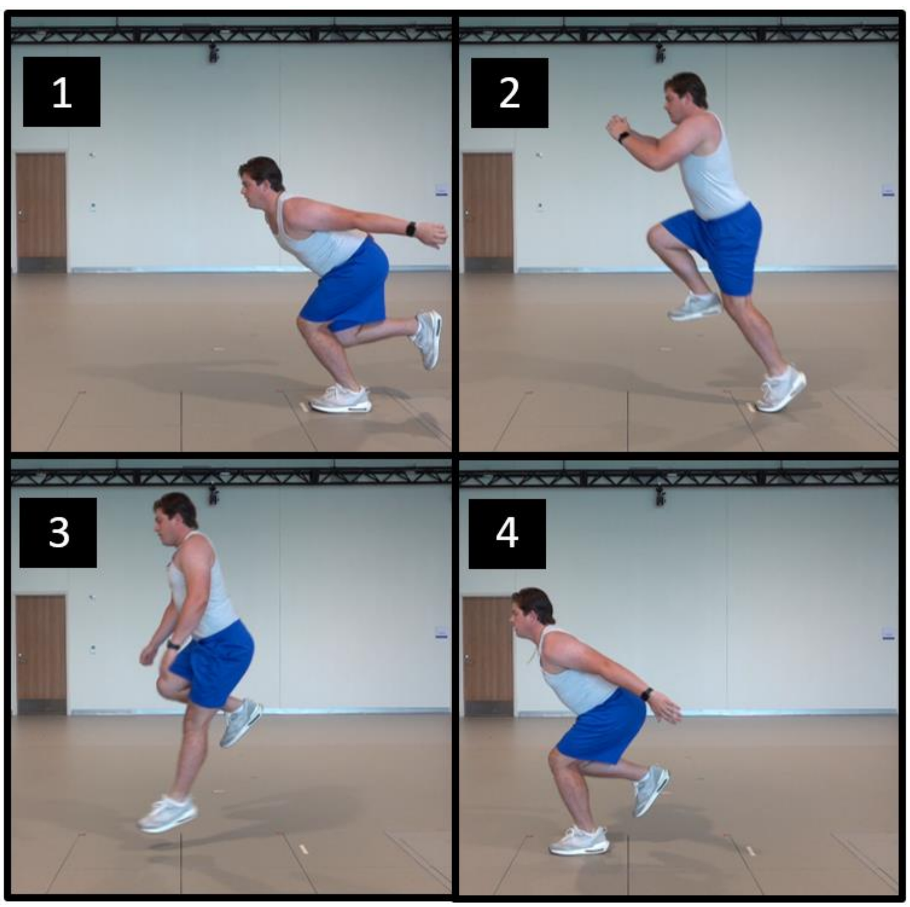


   d. Video cameras placed for front and lateral views (lateral view on side of plant foot, opposite of direction of cut).
2. ***Instructions:***
   a. "Run as fast as you feel comfortable towards the box on the floor. Land with your (right/left) foot inside the box before cutting (left/right). Push off that foot and run as fast as you feel comfortable for 3-4 strides."
      i. Tips:
         - Line up the patient such that their foot will hit the plate naturally, ideally slightly to the side of the box.
         - If the patient plants on either side of the force plate, adjusting Cone 2 along the back edge of the force plate may help align the patient so they naturally plant in the force plate.
         - Perhaps demonstrate what 'rounding' rather than 'cutting' looks like and mention this is incorrect.
   b. Collect 3 trials for each direction.
      i. It is up to the lab on whether three trials are collected for one leg before switching to the other leg, or if collected trials alternate between legs.
3. ***Performance:***
   a. Must plant foot on force plate during cut.
   b. Instruct to perform as fast as possible, with 2-4 running strides after the cut depending on lab space available.

Running Forward	Plant on One Leg	Cut and Run Diagonal

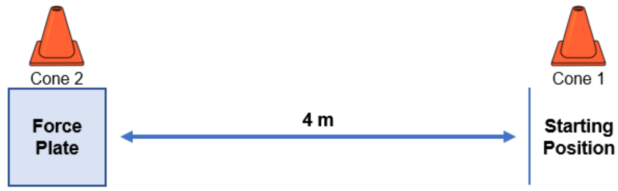
V.f Single Leg Hop – *optional task*

1. ***Set up:***
   a. The patient will stand at the starting position facing towards the landing target (force plate).
   b. Video cameras placed for front and lateral views (lateral view on side of jump limb during landing).
2. ***Instructions:***
   a. "Start by standing on one leg at the starting line. Then, jump forward as far as you can, landing on the same leg. You must stick the landing for at least 3 seconds. If you hop, wiggle, or stutter step, the trial will not count. You will complete 3 good trials on the same leg, then switch sides and repeat."
   b. If needed for return-to-play assessment, measure the distance of each jump manually.
      i. Measure from toe at takeoff to heel at landing between trials. Do not put tape on the floor.
      ii. Distance will also be calculated during post-processing.
   c. Collect 3 trials for each leg landing in the force plate.
      i. Can collect data of patient jumping out of the force plate as well but only trials jumping into the plate will be processed and analyzed.
      ii. Suggested collection strategy:
         - Collect 3-5 trials total taking off out of the plate. Manually record the distance of all takeoff trails.
         - Once the distance plateaus (remains within 10 cm), average the final 3 distances for each leg. Then, calculate 90% of the average.
         - Measure from the closest edge of the force place and place tape at the calculated 90% average max distance. Thus, the patient will jump further than 90% max distance (~100% max) into the force plate.
         - Have the patient start with their toes on the tape and collect 3 trials with the patient landing in the plate.
3. ***Performance:***
   a. Disqualified if landing is not stable for at least 3 seconds.
   b. *Alternative collection strategies:* Jumping out of the plate provides a set starting point for jumping back into plate.



V.g Deceleration – *optional task*

1. ***Set up:***
   a. The distance for the run should be approximately 12 feet long, as space permits.
   b. Patient will start at one end of the "runway" behind a taped starting line, facing forward.
   c. Video cameras placed for front and lateral views (lateral view on side of planting/lead foot).



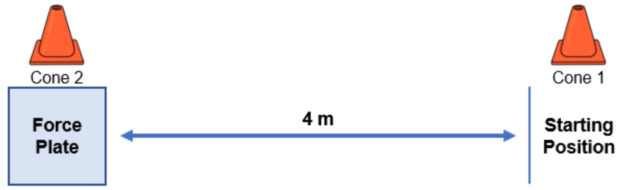
2. ***Instructions:***
   a. "On 'go', you are going to run forward and plant your (left or right) foot into the box, and then backpedal back to the taped starting line. You will be timed so run up and backpedal back as fast as you can. After practicing, repeat this three times in a row without stopping."
      i. Cues:
         - Try to transition quickly.
         - Only one foot in the box. No double taps.
         - Make sure your plant foot is fully in the box from toe to heel.
      ii. Tips:
         - Demonstrate what a tap is verses a plant. Show what not to do.
         - Demonstrate how the back foot should not hit the force plate.
         - Demonstrate how the foot needs to plant fully in the plate.
         - Keep a 'practice-like' environment to maintain motivation. They need to go as fast as they can and be successful. This may involve allowing a slight pause between trials to maintain body control.
         - If space is limited, put a cone a few steps in front of the starting line so that the patient has a visual cue to stop at the appropriate spot and doesn't pass the starting line (and hit the wall).
   b. Collect 3 consecutive trials for each side, with all trials of each plant foot in the same file.
      i. 2 total files, 1 per side.
      ii. Each trial analyzed separately.
      iii. Make sure to record the time for the entire task for each leg (3 consecutive trials).
3. ***Performance:***
   a. Timing the task encourages effort.
   b. If foot placement fell outside of the force plate, ask the patient to perform an additional trial.

Running Forward	Planting with Lead Foot	Running Backward

V.h Heel Touch – *optional task*

1. ***Set up:***
   a. Place a box of the appropriate height (see below) in the center of the lab. The location of the box does not matter, as no force plates will be used.
      i. If patient is ≤155cm tall, use a 6-inch step.
      ii. If patient is >155 cm tall, use an 8-inch step.
   b. Make sure the box will not tip over (i.e., place a weight on top if unstable).
   c. Video cameras placed for front and lateral views (lateral view on side of stance limb).
   d. Patient begins standing on the box with both feet, facing straight ahead. Arm position does not need to be fixed.
2. ***Instructions:***
   a. "Start by standing on the box with both feet. All your weight is going to stay on one leg and you are going to squat down, extend your other leg forward, and tap the floor with your heel. The foot on the step must stay in contact with the step the whole time. Lightly tap the heel of your outstretched leg onto the floor and then come back up to standing. Complete this task "nice and slow" and look straight ahead through the entire task.
   b. Collect 3 trials for each leg.
      i. Collection should start on the unaffected limb to ensure the patient can complete the task successfully.
         - If unsuccessful on the unaffected limb, record best effort trial on each limb.
      ii. It is up to the lab's discretion whether the trials are collected in a single collection file for each leg (2 files total) or in separate files (6 files total).
      iii. Each trial analyzed separately.
3. ***Performance:***
   a. This should be a fluid motion, approximately 1 second down and 1 second up.
   b. Heel should tap ground briefly, but patient should not put body weight through this limb throughout the task.
   c. The outreached heel may return to box if needed before starting next trial.
   d. Stance foot (especially the heel) must remain in contact with box throughout the task.
   e. If this task is too challenging or they look unstable while performing the task, reconsider testing the jump tasks.
4. ***Modification:***
   a. The height of the bench based on the patient's height should be used first. If too challenging, the height may be lowered.

V.i Lateral Shuffle – *optional task*



1. ***Set up:***
   a. The distance for the shuffle should be approximately 12 feet long, as space permits.
   b. Patient will start at one end of the “runway” at a taped starting line, facing sideways.
   c. Video cameras placed for front and lateral views (lateral view on side of planting/lead foot).
2. ***Instructions:***
   a. “This is a lateral shuffle. On ‘go’, you are going to shuffle to the side without crossing your feet until your lead foot hits the box, then shuffle back to where you started. You will be timed so shuffle over and back as fast as you can. After practicing, complete three times in a row without stopping.”
      i. Cues:
         - Try to transition quickly.
         - It is more important to have a controlled transition than a faster speed. Make a solid plant to push off.
         - Only one foot in the box. No double taps.
         - Make sure your foot is fully in the box from toe to heel.
         - Don’t drift backwards or forwards. Shuffle sideways in a straight line.
      ii. Tips:
         - Demonstrate what a tap is verses a plant. Show what not to do.
         - Demonstrate how the foot needs to plant fully in the plate.
         - If plates are smaller, make sure the forefoot is planting closer to the front edge of the plate (relative to the foot).
         - Keep a ‘practice-like’ environment to maintain motivation. They need to go as fast as they can and be successful. This may involve allowing a slight pause between trials to maintain body control.
   b. Collect 3 consecutive trials for each direction, with all trials of each direction in the same file.
      i. 2 total files, 1 per side.
      ii. Each trial analyzed separately.
      iii. Make sure to record the time for the entire task for each leg (3 consecutive trials).
3. ***Performance:***
   a. Timing the task encourages effort.
   b. Patient needs to plant lead foot on force plate.
   c. If foot placement fell outside of the force plate, ask the patient to perform an additional trial.
   d. Feet cannot cross during this task.

V.j Isokinetic Strength Testing – *optional task*

If available, isokinetic strength testing is recommended as a potential screen for whether a patient is eligible for motion analysis testing. If the patient passes the following test based on the listed criteria, the patient is likely safe to complete more dynamic tasks in the lab. If the patient fails any single criterion, motion analysis testing may be reconsidered, and thus, only strength testing will guide further physical therapy. This decision will be at the discretion of each lab.

***Patient must achieve full range-of-motion at the knee to be permitted to perform isokinetic testing.**

<u>Timing of Isokinetic Testing</u>

*Typically, testing will occur 5-7 months' post-operative – This referral is likely surgeon-dependent.

*This test should be performed same day as motion capture testing. If this is not possible, motion capture testing should occur as soon as possible following strength testing.

1. ***Warm up:***
   a. 5-10 minutes on treadmill or bike at self-selected speed
2. ***Position for Testing:***
   a. Hips flexed to 90 degrees
   b. Seat Depth: Popliteal fossa 2-3cm in front of the edge of the seat
   c. Chest, pelvis, and lower extremities secured with straps
   d. Hands hold the handles of the chair
   e. Dynamometer Axis of Rotation: align with femoral condyles
   f. Lever Arm Pad: 2-3 cm proximal to ankle malleoli
   g. Gravity Adjustment: limb weight set with knee at 10-15 degrees of flexion
      i. Potentially set using an alternative method based on the equipment/system used.
   h. Range set for testing: Full extension to full flexion
      i. If the patient does not have full range-of-motion, consider terminating test.
3. ***Verbal Instructions:***
   a. "Motion should only occur at your knee. Please limit any additional trunk or upper body movement."
   b. "Move through the entire motion to bring your knee as straight as possible, then bend your knee until you reach maximal flexion."
   c. Practice trials: "These do not need to be performed at full effort. We want to make sure you are familiar with the test before we begin."
   d. Test trials: "Kick out and pull back as hard and as fast as you can"
      i. Verbal encouragement should be provided through testing.
      ii. Visual feedback on the monitor should <u>not</u> be provided.
4. ***Testing Order:***
   a. Uninvolved limb
   b. Involved limb
5. ***Testing Protocol***
   a. See table for minimum recommendations
      i. Reps per speed at the discretion of individual labs
6. ***Pass/Fail Criteria for Return to Play***
   a. Variable for Assessment: Peak Torque
      i. Quadriceps to Hamstring Ratio: 60-80%
      ii. Involved vs. Uninvolved: < 10%

TRIAL	REPS	EFFORT	SPEED
PRACTICE	3 x 1	50%	300 deg/sec
REST	60 sec		
TEST	15 x 1	100%	300 deg/sec
REST	60 sec		
PRACTICE	3 x 1	50%	180 deg/sec
REST	60 sec		
TEST	10 x 1	100%	180 deg/sec
REST	60 sec		
PRACTICE	3 x 1	50%	60 deg/sec
REST	60 sec		
TEST	5 x 1	100%	60 deg/sec

Section VI: Data Processing

If any of the following recommendations are not adopted, it is highly encouraged to save unprocessed data files allowing the option to follow the recommended procedures at a later time.

VI.a Gap Filling Options

1. ***Rigid Body Fill (Primary Method):***
   a. For segments with at least four markers total, three of which are present (i.e., trunk, pelvis, clusters)
   b. Gaps ≤ 20 frames may be filled automatically through a pipeline.
      i. Larger gaps should be individually assessed visually and filled manually.
2. ***Pattern Fill:***
   a. For segments with three markers (i.e., foot) or when too few markers are present to use rigid body fill
   b. Nearest marker should be automatically used to fill gaps ≤ 20 frames.
      i. Larger gaps should be individually assessed visually and filled manually.
   c. If pattern fill is used to gap fill a marker on a 4-marker segment due too multiple absent markers, transition to using rigid body fill once enough markers have been filled to do so.
3. ***Spline Fill:***
   a. This gap filling option should be a last resort.
   b. Only use for gaps ≤ 5 frames.
   c. 2-camera reconstruction is also an option.

VI.b Data Filtering

1. ***Motion Capture Marker Data:***
   a. Woltring filter – MSE 10 mm^2

2. ***Force Plate Data:***
   a. Butterworth, 4^{th} order, low pass filter – 16 Hz cutoff frequency