

Functional Joints

Functional joints are a method for modelling the joint between two segments according to their apparent relative movement. Functional joints are implemented in Visual3D as an alternative for defining joint landmarks and can be chosen to use in segment definitions if desired. At their core functional joints are simply landmarks. Their use is optional and can be used on a case-by-case basis and can be used in the some model with anatomical landmarks, regression landmarks or functional landmarks. They became popular as a method to reduce errors from marker placement. However, their accuracy is affected by movements performed, range and speed of motion, the participant studied and the soft tissue artifact. As a result, functional joints should used carefully with their results being validated using another anatomical landmarks when possible, making these others methods often more trustworthy.

Data Collection

Using functional joints increases data collection collections and processing time and requirements. More movement trials must be collected specifically to compute the functional joints with movements that can be challenging for certain participants, particularly patient populations. Defining functional joints requires at least 3 tracking markers are required for each segment. These tracking markers should not be near the joint to ensure that the motion measured is truly meaningful for defining the functional axis of the joint. This can mean that additional tracking markers need to be added to track segments if you're using a marker set which was not designed for defining functional joints. The movement trial used is contrived specifically for the purpose of computing the functional joint. It should not be assumed that any particular dynamic movement trial, e.g. a walking trial, is sufficient. Your "functional joint" trial should be separate from the movement data trials

The input movement

Calculating a functional joint requires the movement of one segment relative to another segment. Based on this relative movement the chosen algorithm (see below) searches for a point (or, for a one degree of freedom joint, an axis) that is stationary relative to the 2 segments (or 2 sets of markers).

Three Degrees of Freedom

For joints modelled with 3 degrees of freedom, the chosen movement trial should have the following characteristics:

1. the joint has modest range of motion about all three axes of rotation;
2. the movement should have sufficient range of motion to produce a reasonable stationary point;
3. but the range of motion should also not be too large because soft tissue artifact (e.g. movement of markers relative to the underlying skeleton) should be minimized.

Our experience is that 20 degrees range of motion is usually sufficient to compute a stationary point reliably. Several cycles of movement should be included in the motion, but it isn't clear exactly how

many cycles there should be. We recommend more than 5 cycles, but users should experiment with their own data setups because the optimal number of cycles depends on many issues including: the joint tested and the amount of soft tissue artifact present in the data.

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Begon, Monnet, and Lacouture defined characteristics of the movement profile that should be used for the functional joint calculation, however this is not the only movement profile that is possible. We recommend that users “play around” with other options until they find a movement that is reliable for their subject population.

It is very difficult for many subjects to balance themselves for the functional trials, so many investigators support the subject and move the thigh for the subject. If you are interested in the user actively performing the movement, we recommend a hula movement for the hip joints.

One Degree of Freedom (Functional Axis)

If the joint is precisely one degree of freedom, it is possible to compute an axis, but it is not possible to compute a stationary point. In practice, joints aren't only one degree of freedom, and there is often some soft tissue artifact. This “noise” is then the source of data for computing a stationary point. The closer to one degree of freedom, the less reliable the stationary point.

For the knee joint, we recommend projecting a lateral and medial knee marker onto the functional knee axis.

Algorithms for calculating Functional Joints

Visual3D includes multiple algorithms for calculating functional joints. Regardless of the algorithm chosen, the general approach is to search for a point (or, for a one degree of freedom joint, an axis) that is stationary relative to the joint's 2 segments (or 2 sets of markers).

The Gillette Algorithm

This approach is adapted from: Schwartz MH, Rozumalski A (2005) A new method for estimating joint parameters from motion data. *Journal of Biomechanics*, 38, 107-116.

To begin:

1. specify a segment coordinate system in which the motion capture data is to be resolved and into which the landmark represented. For the case of the hip joint centre, the pelvis is generally considered a stationary coordinate system.
2. specify the motion capture markers attached to the moving segment. For the case of the hip joint centre, markers attached to the thigh are used.

Then, for all combinations of 3 frames (a,b,c) of data from the moving trial:

1. Compute Finite Helical Axis (A) for frames a and b, Finite Helical Axis (B) for frames a and c, and Finite Helical Axis (C) for frames b and c.
 1. Remove any helical axis where the amount of rotation is less than a minimum value (e.g. 5 degrees).
2. Compute the intersection of Axes A & B, of Axes A & C, and of Axes B & C.
 1. Compute the intersection as a line segment that is the shortest route between the two axes. The "intersection" is the mid-point of this straight line and is considered one estimate of the joint centre, e.g. a candidate joint centre.
 2. All candidate joint centres are added to a "candidate array". This candidate array gets very big very quickly because the number of permutations grows dramatically with the number of frames considered.
 3. **NOTE:** With "real" data there is rarely an intersection of the two Finite Helical Axes.
3. Calculate the mode of the candidate array:
 1. **NOTE:** The 3D mode is challenging to compute, so Visual3D estimates the mode. In principle Visual3D would use all candidates, but this is often impractical, so Visual3D samples the candidate array randomly. The number of candidates selected is an option defined by the user.
 2. Compute the mean value of all candidates.
 3. Specify a sphere surrounding this location (the size of the initial sphere is an option defined by the user). A fairly big number is used typically, but the actual value hasn't been found to be particularly important.
 4. While the number of candidates is greater than 500 (a threshold defined by the user)...
 1. The "candidate array" is reduced by removing all candidates that are not in the interior of this sphere.
 2. The median value of each component is computed for the remaining candidates.
 3. The radius of the sphere is reduced (the percent decrease is another user-defined option).
 5. When only 500 candidates remain, the function joint is defined as the mean value of these remaining candidates.
 6. **NOTE:** The number of combinations gets very big very quickly and can easily crash the system if the user isn't careful. An option exists to select a subset of combinations at random (e.g. 2,000,000 combinations) as a representative sample.
4. Return the mode of the candidate array as the joint centre.

The Mayo Algorithm

This approach is adapted from: Jensen, E., Lugade, V., Crenshaw, J., Miller, E., & Kaufman, K. (2016). A principal component analysis approach to correcting the knee flexion axis during gait. *Journal of Biomechanics*, 49(9), 1698-1704.

From the authors' abstract:

Accurate and precise knee flexion axis identification is critical for prescribing and assessing tibial and femoral derotation osteotomies, but is highly prone to marker misplacement-induced error. The purpose of this study was to develop an efficient algorithm for post-hoc correction of the knee flexion axis and test its efficacy relative to other established algorithms. Gait data were collected on twelve healthy subjects using standard marker placement as well as intentionally misplaced lateral knee markers. The efficacy of the algorithm was assessed by quantifying the reduction in knee angle errors. Crosstalk error was quantified from the coefficient of determination (r^2) between knee flexion and adduction angles. Mean rotation offset error (α_0) was quantified from the knee

and hip rotation kinematics across the gait cycle. The principal component analysis (PCA)-based algorithm significantly reduced r^2 ($p < 0.001$) and caused α_{knee} to converge toward $11.9 \pm 8.0^\circ$ of external rotation, demonstrating improved certainty of the knee kinematics. The within-subject standard deviation of α_{hip} between marker placements was reduced from $13.5 \pm 1.5^\circ$ to $0.7 \pm 0.2^\circ$ ($p < 0.001$), demonstrating improved precision of the knee kinematics. The PCA-based algorithm performed at levels comparable to a knee abduction-adduction minimization algorithm (Baker et al., 1999) and better than a null space algorithm (Schwartz and Rozumalski, 2005) for this healthy subject population.

Limitations

Functional joint can fail with no obvious indication of failure other than unreasonable joint locations. Many laboratories compare functional joint estimates against anatomical landmarks or regression-based estimates to identify failed calculations. However, there is no defined threshold for determining when a functional joint calculations are incorrect. The results are often rejected when the values differ substantially from anatomical estimates.

Functional Knee Axis Warning: The functional knee axis is not the flexion/extension axis of your knee angle. Visual3D (and most software) use right handed orthogonal coordinate systems. The z-axis (axial direction) is defined by a vector between the distal and proximal ends of the segment. The x-axis lies in the frontal plane, but is forced to be perpendicular to the z-axis, which is unlikely to be parallel to the functional knee axis (it is just in the same plane). Mathematically the functional axis computed has no direction. It could point medial or lateral to the segment, but the algorithm doesn't have enough information to know the correct direction.

Examples

See these examples for computing and working with functional joints in Visual3D:

- [Defining a functional joint](#)
- [Post-processing for functional joints](#)
- [Add a Functional Joint landmark](#)
- [Compute a Functional Hip Joint](#)
- [Compute a Functional Knee Joint](#)

References

1. Begon M, Monnet T, Lacouture P (2007) Effects of movement for estimating the hip joint center. *Gait and Posture* 25, 353-359. [DOI](#)
2. Jensen, E., Lugade, V., Crenshaw, J., Miller, E., & Kaufman, K. (2016). A principal component analysis approach to correcting the knee flexion axis during gait. *Journal of Biomechanics*, 49(9), 1698-1704. [DOI](#)
3. Schwartz MH, Rozumalski A (2005) A new method for estimating joint parameters from motion data. *Journal of Biomechanics*, 38, 107-116. [DOI](#)

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