Validation of the Moven Motion Capture System

A study performed
by The University of Iowa's Virtual Soldier Research Program
for The Aberdeen Testing Center

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Executive Summary

Results

- Results were evaluated for 1) differences in relative values (range of values) for the two systems, 2) differences in trends for the two systems, and 3) drift.
- The Moven system has produced acceptable motion, assuming that proper care is taken when using the system. Nevertheless, consistent with the literature, the Moven system can demonstrate difficulties with drift in the global position of the avatar/subject.
- The Moven system showed acceptable performance with respect to measuring relative motion but potentially poor performance with respect to global position. This could present an especially significant problem when monitoring multiple subjects simultaneously.
- In general, Moven system acts as if avatar should remain at same vertical level. The smooth and consistent global lateral motion shown with demonstrations was not reproducible.
- There was some, but minimal drift with the exception of the jumping task during which there was substantial drift, which seems to come into play when both feet are off the ground.
- There was minimal distinct effect from metal with walking, but some issues when metal was close to sensors
- There were minimal issues directly related to twisting motion, although both systems had well acknowledged and typical difficulties in accurately representing the shoulder complex
- In most cases, there were minimal differences in recorded motion trends
- There were unexplained differences between the 5th percentile and 95th percentile subjects, possibly a result of the frequency with which the Moven system was calibrated
- Calibration is significant. Results can be sensitive to the frequency and care with which the system is calibrated.
- When the direction of walking is different from direction the subject is pointed in when calibrating, there can be odd results when looking at global position trends.

Purpose

- Compare the accuracy and repeatability of the Moven inertial system to a Motion Analysis marker-based system
- Investigate the surfacing of the following potential issues: 1) drift with extending motion such as walking, 2) artificial motion and drift during impact at relatively fast speeds as with jumping, 3) interference with metals such as walking across force plates, and 4) the ability of the system to capture twisting motion of the arm accurately.

Method

- 2 subjects: 5th percentile and 95th percentile
- Four tasks: extended walking, jumping, walking over metal, and arm twisting
- Objectively evaluate metrics for each task plotted over time for each motion system
- Subjectively evaluate animated results from the Moven system

Future

- Test arm twisting motion with arms hanging straight down
- Consider additional subjects
- Process additional data, which was gathered during this study: sitting, standing, head twisting, arm raises, and running
- Additional experimentation with settings/parameters for the Moven software
- Additional experimentation with synchronizing global coordinate systems
- Use of the C3D file format available with new versions of the Moven software

Introduction

According to the literature (1-5), the Moven system is considered a new technology that has great potential in applications where it is impractical to use other current motion-capture systems such as the marker-based systems (i.e. Motion Analysis, Vicon, etc.). Still, the literature suggests that the Moven system, as do other inertial systems, has limitations with some applications, one of the most significant being its tendency to drift with extended motion. Xsens, the manufacturer of the Moven system, is aware of these limitations and has addressed them in the user manual with recommended settings and processes. However, this can require different protocols for extended tasks that involve multiple subtasks (and associated potential issues). In addition, some of these recommendations require the user to recalibrate the Moven system frequently, which can be time consuming and awkward, especially with extended tasks. The primary intent of this study is to compare the performance of the Moven suite to marker-based systems. In doing so, all recommendations in the manual are followed. No effort is made to judge or evaluate the system as to whether or not it should be used. Rather, its performance is evaluated relative to marker-based systems from a scientific perspective.

The Moven system is tested under specific conditions that are expected to shed light on potential difficulties with the system, as well as conditions that are essential to the ATC applications. These conditions include: 1) drift with extending motion such as walking, 2) artificial motion and drift during impact at relatively fast speeds as with jumping, 3) interference with metals such as walking across force plates, and 4) the ability of the system to capture twisting motion of the arm accurately. The results from Moven system are compared with a baseline Motion Analysis system (Motion Analysis Corporation, Santa Rosa, CA, USA, http://www.motionanalysis.com/index.html). This assumes that the Motion Analysis system is reasonably accurate; it is well accepted as a method for tracking motion. The motion analysis data are post-processed using NIH approved Visual3D software (C-Motion, Inc, Kingston, ON, Canada, http://www.c-motion.com/).

This report summarizes the findings of these experimental comparisons. It is assumed that the baseline results provided by Motion Analysis and Visual 3D are accurate and repeatable. The Moven system was calibrated according to the manual, and data from the Moven system were exported into a BVH format.

The Validation Plan

The general test plan followed the original proposal and is outlined as follows:

a. Subject preparation: Two subjects were used in this comparison process, one in the 5th percentile range and one in the 95th percentile range. The percentile was determined based on overall subject-height. The subjects wore the Moven system suit according to their sizes. Reflective markers were attached to the subject bodies according to the Motion Analysis and Visual3D marker protocols.
b. IRB approved from UI (an existing IRB approval was used)
c. Data gathering: the data were gathered for extended walking, interaction with metals, isometric jumping, and body-segment twisting.

d. The Motion Analysis data were post-processed using Visual3D software. The data were exported as text files.
e. The Moven data were exported as BVH files and were changed to text files. Axis orientations and directions were transformed into the same space as Visual3D.

With respect to file import/export, the initial plan was to export C3D files from Moven system and Motion Analysis system, and import these data intoVisual3D, where the comparison would be done. However, VSR has not received the C3D composer, and in order to save time, the data were exported from Moven using the BVH format. The BVH files were then transformed to text files using Matlab. The Moven BVH files include information about the relative joint angles between the adjacent body-segment and the global position of the pelvis.

A primary difficulty when comparing files from Moven and Visual 3D is the inconsistency between the orientation and direction of the local coordinate systems for body-segments. Therefore, a special customized-skeleton was built inside Visual 3D in order to export the joint angles in the same rotation order as Moven. This was especially important for the complex shoulder joint.

Results

This section presents the results for the following four tasks: extended walking, jumping, walking across metal, and arm twisting. For each task, to avoid having to compare a large number of degrees of freedom, a limited number of comparison determinants were selected. In general, these determinants provide the minimum number of metrics necessary to characterize uniquely a motion or posture. The determinants for each task are detailed along with the discussion of the task-related results.

The data for these results are presented in a series of plots. For each task and each metric, one plot is shown for the 5th percentile subject and for the 95th percentile subject. When appropriate, indices indicate data gathered during various stages of a task. For instance, “Moven-1” indicates Moven data gathered during the beginning of a task, whereas “Move-3” indicates data gathered during the end of a task. Thus, any difference in these sets of data suggests variation or drift in the system.

With respect to the global coordinate systems, there was no way to ensure that both motion systems had the global coordinate system located in the same lateral location, although they did have the same orientation. Consequently, it is not possible to evaluate the absolute accuracy of the Moven system in tracking global position and orientation, but it is possible to track drift in this regard. Given the arbitrary location of the global coordinate systems, curves showing results for global position were shifted in order to show results for both motion systems using similar scales. However, this is not the case for global vertical position, because the floor provides a common reference point.

With respect to local determinants, because of differences in local coordinate systems for the two systems, it is difficult to compare directly the absolute values for various determinants. Rather, the trends and the relative values (ranges) are compared between the two systems. For example, in Figure 4, although the results for the two systems show a shift difference of approximately twenty degrees, the trends are the same, and the changes in angle for each system are the same.

Drift is generally indicated by a change in the distance between a curve showing Moven data (i.e. Moven-1) and a corresponding curve showing Visual 3D data (i.e. Visual3D-1). Drift is also demonstrated in the case of medial-lateral global position, when the position for eth end of a curve is substantially different from the position of the beginning of a curve (i.e. Figures 2 and 16).

Note that during the calibration process, the subjects were asked to stand with their feet approximately twelve inches apart. It was later determined that the protocol may have suggested that the subjects feet be one foot width apart. The instruction were unclear in this regard, but the consequence is likely negligible.

In general, it was found that the frequency with which the Moven system is calibrated can be critical. Because the 5th percentile subject was tested after the 95th percentile subject, based on experience, the calibrations were conducted more frequently with the 5th percentile subject.

When reviewing the data, attention was paid to 1) differences in values for the two systems, 2) differences in trends for the two systems, and 3) drift.

1. Extended Walking

Task Description

The extended walk task was designed to investigate the progress in the drift magnitude during the task. The subjects were instructed to walk in one direction, turn around, and return back to the original starting position. Three cycles were considered and shown for the beginning (when the subject starts walking), middle (the subject has walked for many cycles, and is in the middle of the task), and end (after the subject has walked for several cycle, and is ready to stop) of the extended trial. Each cycle was considered to represent steady state walking. This allowed the trend variation over time and drift to be analyzed. On each of the graphs discussed in the following section, the following key frames were indicated: Right Heel Strike (RHS), when the heel hits the floor during the waling cycle; Left Heel Strike (LHS); Right Toe Off (RTO), when the right toe leaves the floor during the walking cycle; and Left Toe Off (LTO). The following determinants were chosen for comparison purposes: pelvic Anterior-Posterior articulation, pelvic Medial-Lateral articulation, Vertical global pelvic position, Hip flexion-extension, Knee flexion-extension, and Ankle plantar-dorsiflexion.

Task Results

Figure 1 shows the characteristics of the Anterior-Posterior global position of subjects using Visual 3D (Motion Analysis) and Moven during the beginning of the walking, the middle of the walking, and at the end of the walking. These results do not show any significant differences between the Moven and the Visual 3D systems, with regards to motion trends or position values.

Figure 2 depicts the Medial-Lateral global position for Visual 3D and Moven. The general downward slope in the curves for the Moven system could possibly be a result of the actual walking direction varying slightly from the direction in which the subject was pointed during the calibration process. It can also indicate drift. The largest range of variation in Moven occurred with the 95th percentile subject at the beginning of the walking cycle representing approximately 2.5 cm. Moven displayed approximately 6.0 cm of variation at the same time based on cycles taken from the beginning, middle, and end of the extended trial. This figure illustrates a clear difference in trends between the two systems. Note that because it refers to a metric for global position, the actual difference in values between the results from the two systems is not relevant.

Figure 3 shows the Vertical global position for Visual 3D and Moven. Some differences are noted between Visual 3D and Moven in the 95th percentile subject. Two such differences can be seen at frames 20 and 80, where the onset of each difference corresponds closely to the right and left toe-off landmarks, respectively. The toe-off landmark can be seen at approximately 10 frames after each heel strike. For the 5th percentile subject this difference was not seen. These fluctuations in vertical position surface with other results as well, and may be due either to a calibration error in the Moven system or to the impact between the subject foot and the floor.

Figure 4 shows the Hip flexion determinant for Visual 3D and Moven. As with figure 3, Figure 4 also displays two slight localized trend changes at frames 20 and 80 for the 95th percentile subject. However, in general, the trends are similar.

Figure 5 depicts the Knee gait determinant for Visual 3D and Moven. For both subjects, there were no significant differences in the resulting knee motion using the two systems.

Figure 6 shows the Ankle gait determinant for Visual 3D and Moven. Consistent with Figure 3 and 4, some variations are seen at approximately frame 20 and 80 in the 95th percentile subject.

Figures 7 and 8 both relate to movement in the pelvis, which provides a common and well accepted metric for walking motion analysis. However, with the tasks considered for this study, other than jumping, pelvic motion is relatively small. Thus, as indicated by the scales on these plots, differences in value between the two motion systems are relatively small. Also note that pelvic tilt and rotation represent global motion and thus, may be subject to drift.

Figure 7 demonstrates the Lateral pelvic tilt gait determinant for Visual 3D and Moven. For the 95th percentile subject some variations are seen following the toe off of the gait cycle, consistent with previous figures. A visually identifiable dip motion was seen in Moven Studio software corresponding to the motion localized around frame 80. Here, the range of motion for this determinant is seen as 5 degrees for Visual 3D and 17 degree for Moven. This could be a result of sensor placement on the ankle, instructions for which were not clear. The 5th percentile subject did not present the identifiable dip in Moven Studio, but does show discontinuities in the data.

Figure 8 shows the Pelvic rotation gait determinant for Visual 3D and Moven. With the 95th percentile subject, Moven and Visual 3D show an approximate range of motion of 15 and 8 degrees, respectively. Over time, the initial pelvic rotation value at the beginning of each gait cycle for Moven displays a range of 6 degrees, whereas Visual 3D displays a range of 2 degrees, thus illustrating some drift.

Figure 8 also illustrates some non-smooth results from the Moven system which could be a result of issues with the filtering system, but further investigation is needed to understand this issue completely.

General Conclusions

In general, the results show that the Moven system can generate non-smooth motion with extended walking, especially at the locations at the heel strikes and the toe-off times. The results indicate minimal drift in the Moven system. There were inconsistencies in the Moven results (with respect to trends) between the 5th percentile and the 95th percentile subjects. The latter could be related the Moven calibration. There is little difference in trends between the two systems, with the exception of Figure 2.

2. Isometric Jumping

Task Description

For the isometric jumping task, participants were instructed to rapidly jump in place for twenty cycles with their elbows bent 90 degrees and their upper arms held at their side. This task was designed to (i) test the capability of Moven to adjust the drift in its global position while the subject is going up and down continuously, (ii) investigate the effect of impact on the sensor movements (due to their relatively large mass when compared with the light reflective markers) and how that would affect the resulting motion, and (iii) study the effect of relatively fast movement on the drift adjustment in Moven. Three cycles are shown for the beginning, middle, and end of the jumping task. This allowed the trend variation over time and drift to be analyzed. Key frames are indicated on the associated plots for Heel Off (HO), the initiation of the jump; Toe Off (TO), beginning of the flight phase; Toe Strike (TS), beginning of the landing phase; and Heel Strike (HS), end of the jump. The following determinants were chosen for the comparison purposes: Anterior-Posterior, Medial-Lateral, and Vertical global position of the pelvic; Shoulder flexion; Elbow flexion; and Trunk flexion.

With this task, a single cycle (labeled for instance as "Moven-1") represents a single jump.

Task Results

Figures 9 and 10 both indicate significant drift. Figure 9 shows the Anterior-Posterior global position for Visual 3D and Moven. It can be seen that Visual 3D's initial anterior position varied less than 20 cm between repetitions for both the 5th and 95th percentile subject. Moven displayed a variation of 1.6 and 0.6 m for the 5th and 95th percentile subjects, respectively, thus indicating a significant drift in the motion.

Figure 10 depicts the Medial-Lateral global position for Visual 3D and Moven. Here, Visual 3D displayed ranges (drift) below 5 cm for both subjects. Moven's initial range was found as approximately 60 cm for the 5th percentile subject and 30 cm for the 95 percentile subject. This again indicates a significant drift in the motion.

Figure 11 shows the Vertical global position for Visual 3D and Moven. The Moven system showed less motion (smaller range) in the global sense than Visual 3D, especially for the 95the percentile subject.

Figure 12 shows the Shoulder flexion determinant for Visual 3D and Moven. In general the Moven system showed consistency and good correlation with Visual3D with regards to overall trends and range of motion.

Figure 13 depicts the Elbow flexion determinant for Visual 3D and Moven. Moven showed good correlation for the two subjects with respect to rends and range of motion.

Note that one would expect relatively little variation in shoulder and elbow flexion during jumping motion.

Figure 14 shows the Trunk flexion determinant for Visual 3D and Moven. In this case, Moven have shown un-normal sudden peaks at the time where the toe strike the floor, especially with the 95^{th} percentile subject. This inaccuracy could possibly stem from the impact during the landing portion of a jump. Regardless of these peaks, there is a difference in the trend of the recorded data for the 95^{th} percentile subject, for the two motion systems. With both subjects there is a significant difference (approximately 20 degrees) in recorded values between the two systems.

Note that the Moven software models the spine/trunk as four distinguishable joints, whereas the Visual 3D system models the spine/trunk with a single joint.

General Conclusions

The results with this task indicate significant drift in the results for the Moven system (Figures 9 and 10). Subjective evaluation of the results also show that body segments, such as the foot, which are close to the floor (the impact source), are more prone to irregularities than the segments that are away from the impact position, such as the elbow and the shoulder.

3. Walking over Metal

Task Description

For the walking over metal task, a ferrous metal plate was placed on the walk way, and the subjects took three steps. The yellow shading in the plots highlights when the subject is in contact with the metal. Key frames are indicated on the plots for Right Heel Strike (RHS) and Left Heel Strike (LHS). The following determinants were chosen for the comparison purposes: Anterior-Posterior, Medial-Lateral, and Vertical global positions of the pelvic; Hip flexion-extension; Knee flexion-extension; Ankle plantar dorsiflexion; Lateral pelvic tilt; and Pelvic rotation.

Note that the 5^{th} percentile subject did not walk over the metal plate completely during the second cycle. Consequently, only results for a single cycle are shown.

Task Results

Figure15 shows the Anterior-Posterior global position for Visual 3D and Moven. No significant differences can be noticed from this graph. There was a close correlation between the Moven and Visual 3D results, and there was no apparent disturbance from the metal.

Figure 16 shows the Medial-Lateral global position for Visual 3D and Moven. As with the extended walking task, the decrease/decline in eth Moven-related curve could result in part from drift and in part the actual walking direction varying slightly from the direction in which the subject was pointed during the calibration process. Note that the 5^{th} percentile subject began with a right-heel-strike, whereas the 95^{th} percentile subject began with a left-heel-strike.

Figure 17 depicts the Vertical global position for Visual 3D and Moven. Compared with normal walking, no apparent difference in the vertical global position was observed from walking over the metal plate. However, the 95^{th} percentile subjects has shown some irregularity at the time of the right and left heel strike, which could be a result on interference from the metal plate.

Figure 18 shows the Hip flexion for Visual 3D and Moven. Note the 5th percentile subject begins with the RHS, and the 95th percentile subject begins with the LHS. Data is taken from the left leg for both subjects. The figure shows no significant differences.

Figure 19 depicts the Knee gait determinant for Visual 3D and Moven. The figure shows no significant differences.

Figure 20 shows the Ankle gait determinant for Visual 3D and Moven. The figure shows no significant differences in overall trend, but there is a significant difference in the range following the RHS for the 95th percentile subject.

Figure 21 shows the Lateral pelvic tilt gait determinant for Visual 3D and Moven. This figure shows considerable irregularities in the Moven motion. Given the nature of pelvic motion, and when coupled with subjective evaluation of the visual results, this data points to difficulties the Moven system can have in adjusting global position.

Figure 22 shows the Pelvic rotation gait determinant for Visual 3D and Moven. The 95th percentile subject showed a phase shift between Moven and Visual 3D for pelvic rotation, but the 5th percentile subject displays no phase shift between the two systems.

General Conclusions

The data for this task further suggests that there can be difficulties in adjusting global position (Figures 16, 21, and 22). With most of the determinants, there seems to be minimal effect from metal, but a slight variation in Figure 16 and irregularities in Figures 17 and 21 suggest that interaction with metal can increase the irregularity in the motion, especially with respect to metrics related to global position/rotation (pelvic rotation and pelvic tilt).

4. Arm Rotation (Twisting)

Task Description

For the arm rotation task, the subjects were instructed to rotate through the full range of motion of their right upper extremity using forearm pronation-supination and arm rotation. Data is presented for the 5th percentile subject holding their upper extremity to the side and for the 95th percentile subject holding their arm to the front. The subjects were instructed simply to rotate their arm; there was no stipulation as to whether this motion should occur at the shoulder or at the wrist/elbow.

The Visual 3D model was modified for the shoulder and elbow to match the axes definitions of the Moven model. In addition, the Visual 3D joint angles for the shoulder and elbow were exported using the YXZ rotation order convention matching the BVH format in which Moven data was obtained. Key frames are indicated on the plots for Full Supination (Sup) and Full Pronation (Pro).

The following determinants were chosen for the comparison purposes: Anterior-Posterior, Medial-Lateral, and Vertical global positions of the pelvic; Shoulder flexion-extension; Shoulder abduction-adduction; Shoulder rotation; Elbow flexion-extension; and Wrist pronation-supination.

Task Results

Figure 23 shows the Anterior-Posterior global position for Arm rotation cycle from Visual 3D and Moven at the 1-beginning, 2-middle, and 3-end rotations. No significant differences in motion trends are shown. Figure 24 depicts the Medial-Lateral global position for Arm rotation cycle from Visual 3D and Moven at the 1-beginning, 2-middle, and 3-end positions. Figure 25 shows the Vertical global position for Arm rotation cycle from Visual 3D and Moven at the 1-beginning, 2-middle, and 3-end positions. As one would expect, there is relatively little motion for the global position of the body with this task.

Figure 26 shows the Shoulder flexion determinant for Visual 3D and Moven at the 1-beginning, 2-middle, and 3-end positions. With both subjects there is substantial fluctuation in shoulder flexion, although one would expect articulation in this direction to be relatively low with this task. Nonetheless, there is little apparent drift, and both motion systems yield similar results.

Figure 27 demonstrates the Shoulder abduction determinant for Visual 3D and Moven at the 1-beginning, 2-middle, and 3-end positions. Although there is likely some shoulder abduction with this task, the plots in this figure indicate much greater articulation than expected. As with shoulder flexion, this is a result of the difficulty in tracking motion for a joint as complex as the shoulder, and this difficulty surfaces with both motion systems.

Figure 28 shows the Shoulder rotation determinant for Visual 3D and Moven at the 1-beginning, 2-middle, and 3-end positions. With both subjects, and especially with th 95th percentile subject, the Moven system showed a much lower (range of) rotation angle.

Figure 29 shows the Elbow flexion determinant for Visual 3D and Moven at the 1-beginning, 2-middle, and 3-end positions. Both systems provide questionable results with elbow flexion. Visual 3D indicates flexion of approximately 20 degrees and 70 degrees with the two subjects. The Moven system indicates flexion of 140 degrees and 100 degrees with the two subjects. Further investigation is necessary to fully explain these results.

Figure 30 shows the Wrist pronation determinant for Visual 3D and Moven at the 1-beginning, 2-middle, and 3-end positions. No significant differences are presented in this figure.

General Conclusions

It can be difficult to compare the performance of the two systems with respect to the shoulder joint (Figures 26 and 27) because of the dissimilarities in the local and global coordinate systems for the two systems. However, the results have indicated that the range of motion obtained from Moven, especially for the elbow joint, is significantly lower than that for Visual 3D. There is little drift with this task.

Additional Discussion

In addition to objective data regarding the determinants for each task, the visual results were studied and evaluated. Subjective finding are summarized as follows.

For the extended walking task, the Moven character showed unnatural motion in the vertical direction. This is likely a result of the Moven system correcting the character global position by minimizing the drift from the initial starting position relative to the ground level. Figure 2 shows that the drift progresses with time and reaches 18 cm in the Medial-lateral direction for the 95th percentile subject but with less drift for the 5th percentile subject. The Moven system also showed abnormal behavior for both subjects for the lateral Pelvic tilt and the pelvic rotation as shown respectively in Figures 7 and 8. The latter abnormalities occurred approximately at LTO.

With jumping, it was clear that the Moven avatar was moving forward a considerable amount, whereas the real subject was jumping up and down on the same spot. In this case, the Moven system may have difficulties adjusting the drift in the global positions relative to the floor due to the fast unanticipated whole-body motion. This subjective finding with jumping-induced drift is consistent with Figure 9, where there was a clear drift in the Anterior-Posterior direction for both subjects. For the 95th percentile subject, the subject started from a position approximately 2.1 meters in the beginning of the jumping task, then moved in the anterior direction to 1.7 meters around the 10th cycle of the jumping, to around 1.4 meters during the last cycle with a total drift of 70 cm. The 5th percentile subject showed similar characteristics with a total drift of 170 cm. The motion of the actual subject was approximately 15 cm from the starting position. Similar drift occurred in the Medial-Lateral direction of 60 cm as shown in Figure 10.

When the subject was walking across the force plate or interacting with metallic objects, the green circles in the Moven character at some places were shaded towards red, indicating some inherent inaccuracies. Accordingly, Figures 21 and 22 show the instability in lateral pelvic tilt and the pelvic rotation respectively.

The two systems showed comparable results for the arm twisting test, except in the case of the shoulder complex. Due to the complexity of the shoulder joint, it was difficult to transform the two systems such that they could be compared directly, as shown in Figure 27.

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Figures

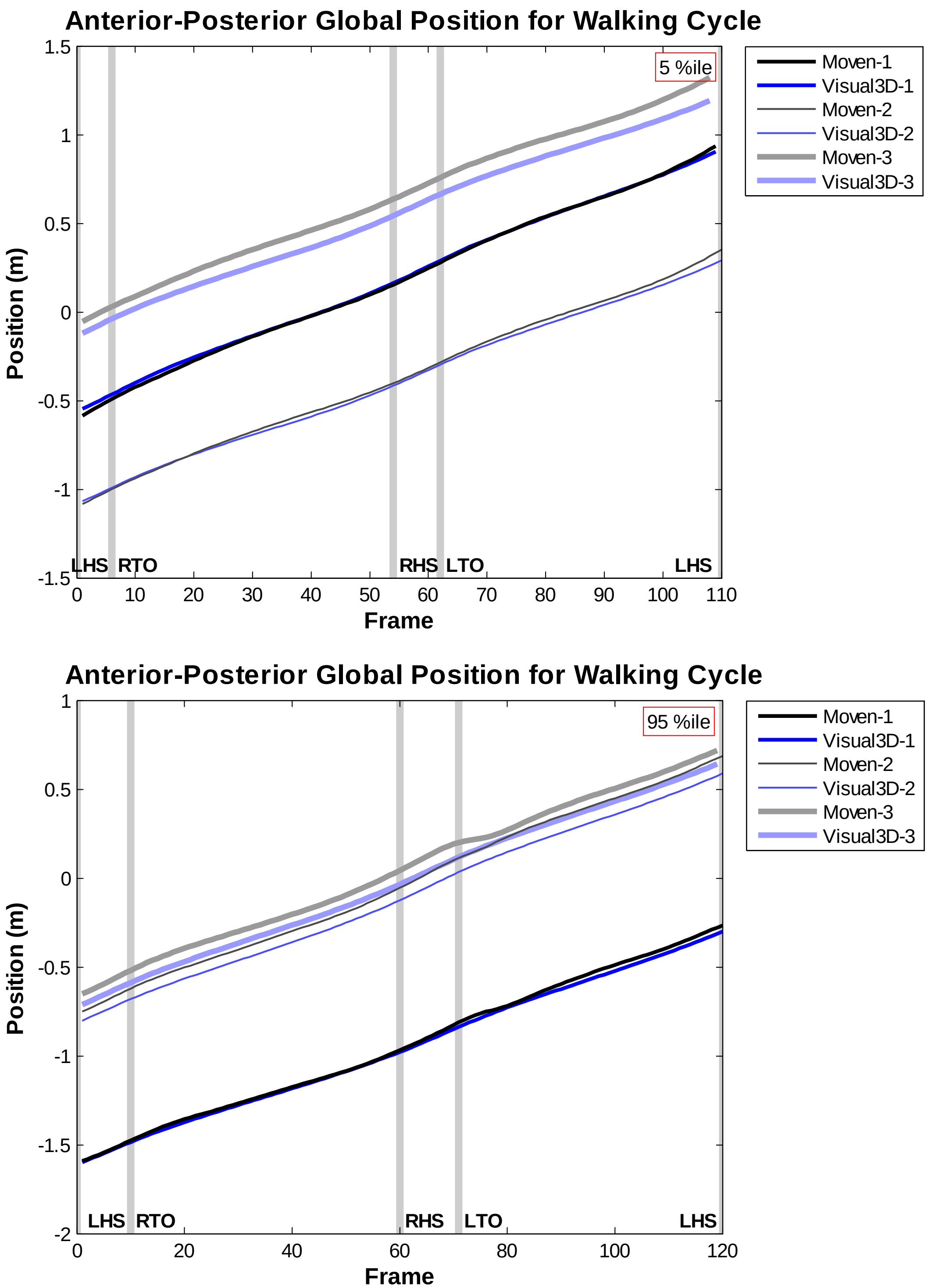


Figure 1 – Anterior-Posterior global position for Visual 3D and Moven (1-beginning, 2-middle, 3-end).

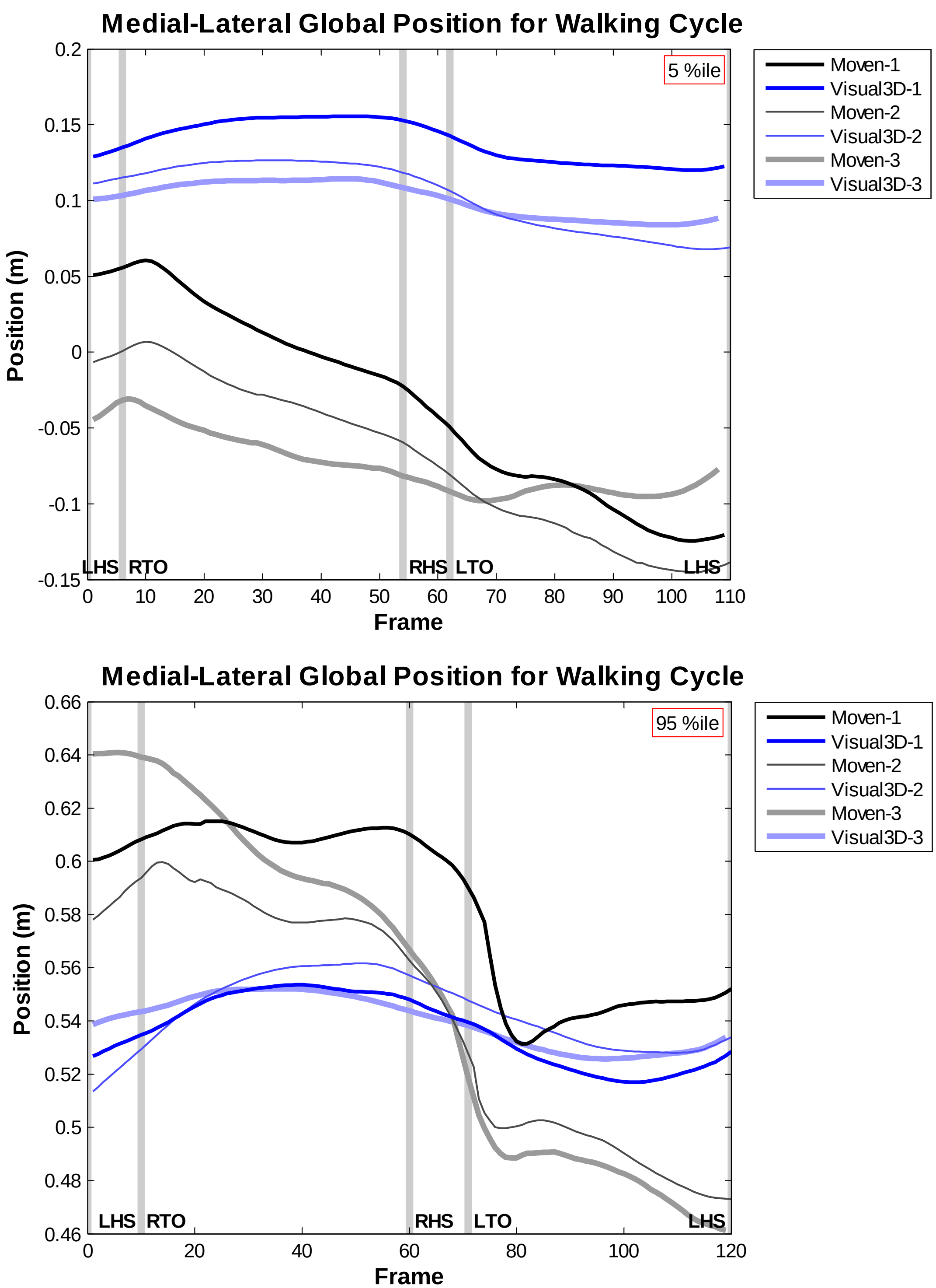


Figure 2 – Medial-Lateral global position for Visual 3D and Moven (1-beginning, 2-middle, 3-end).

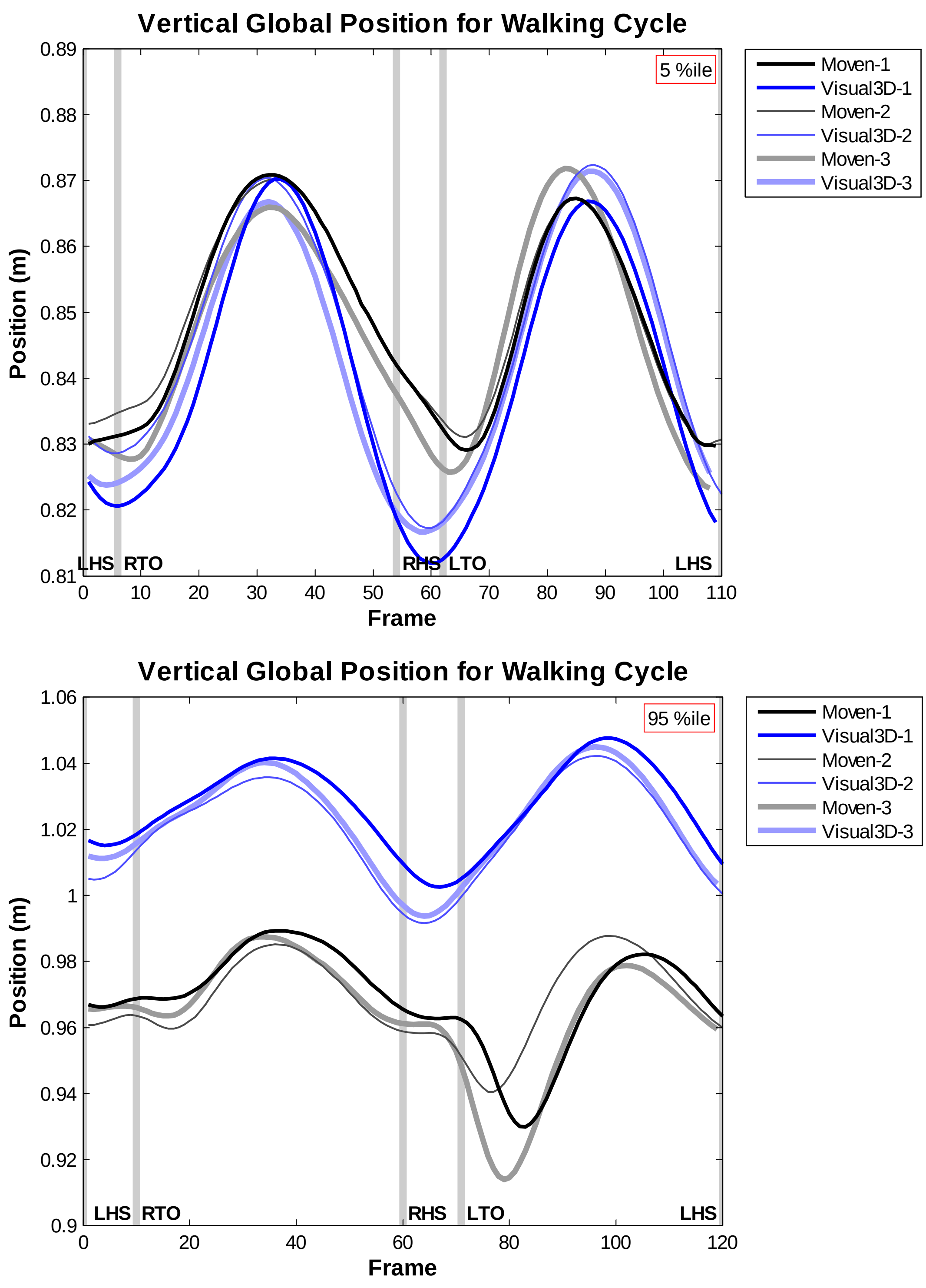


Figure 3 – Vertical global position for Visual 3D and Moven (1-beginning, 2-middle, 3-end).

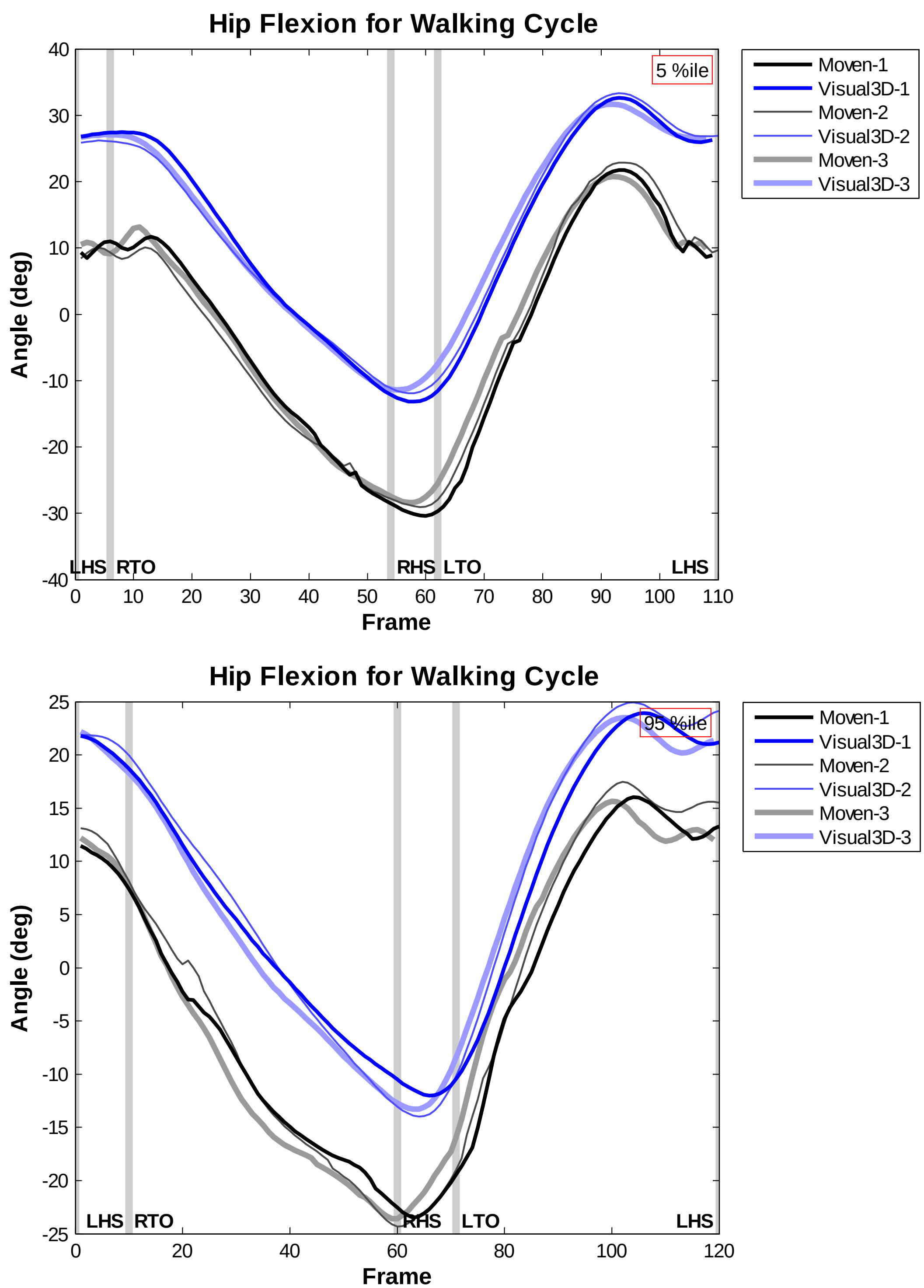


Figure 4 – Hip flexion determinant for Visual 3D and Moven (beginning, middle, end).

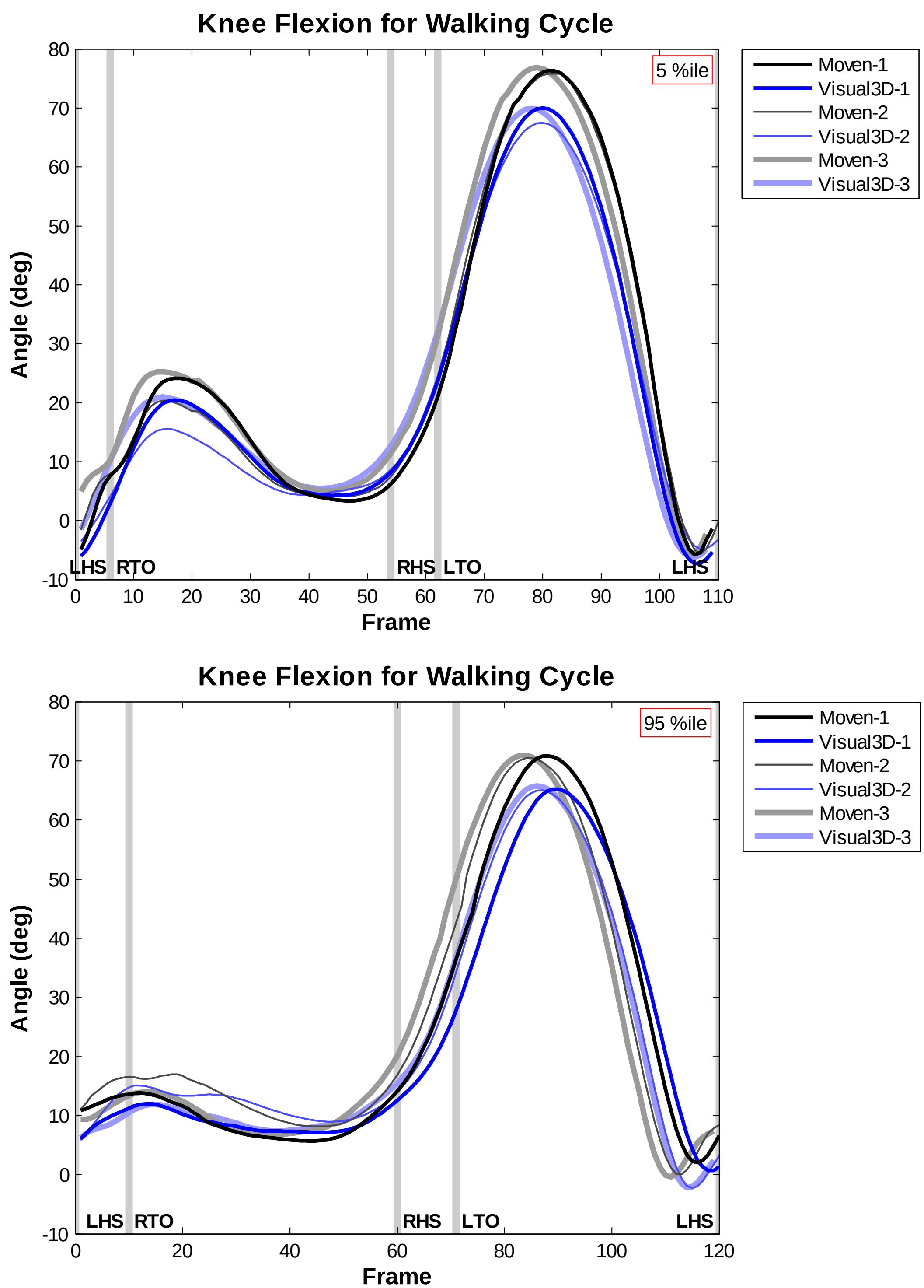


Figure 5 – Knee gait determinant for Visual 3D and Moven (beginning, middle, end).

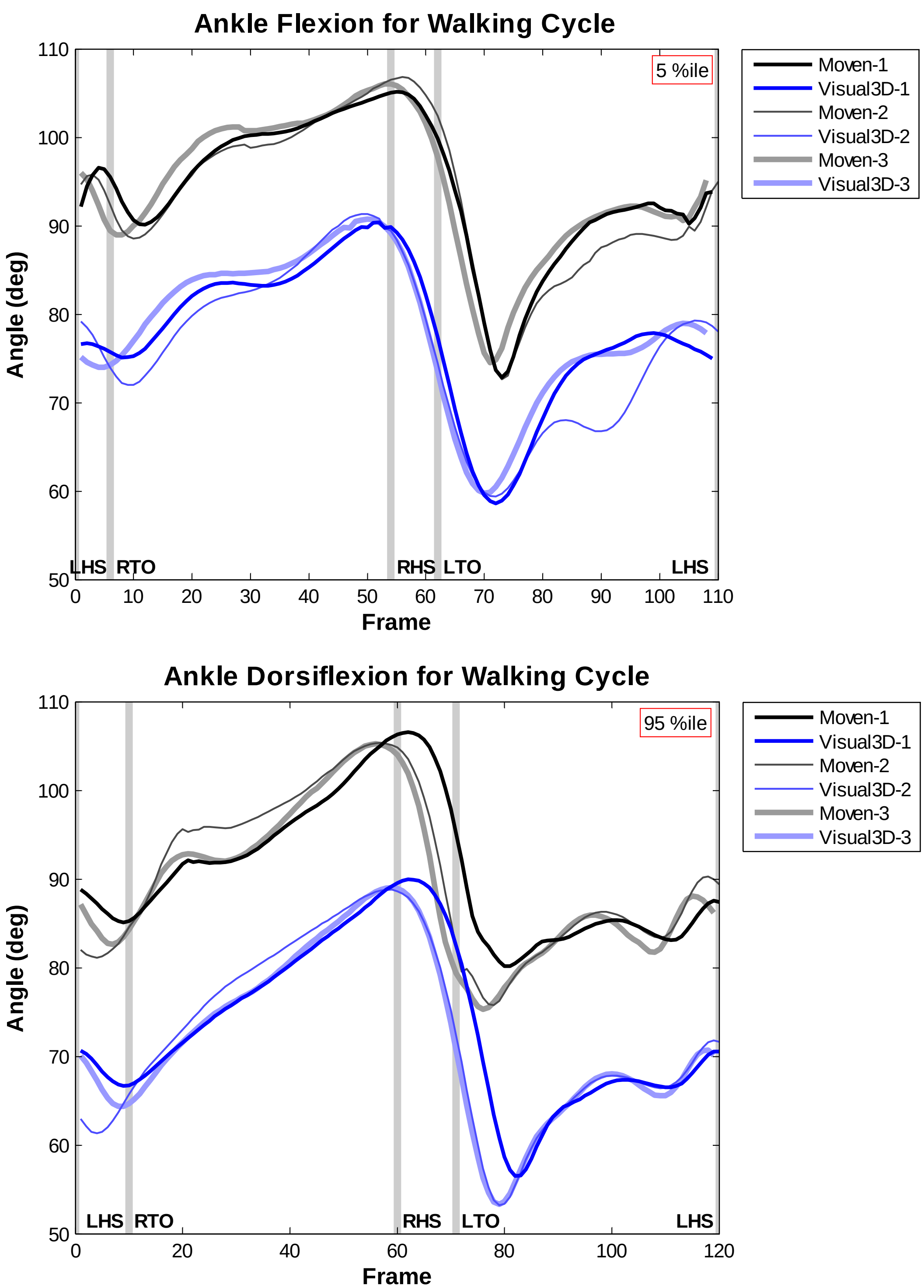


Figure 6 – Ankle gait determinant for Visual 3D and Moven (beginning, middle, end).

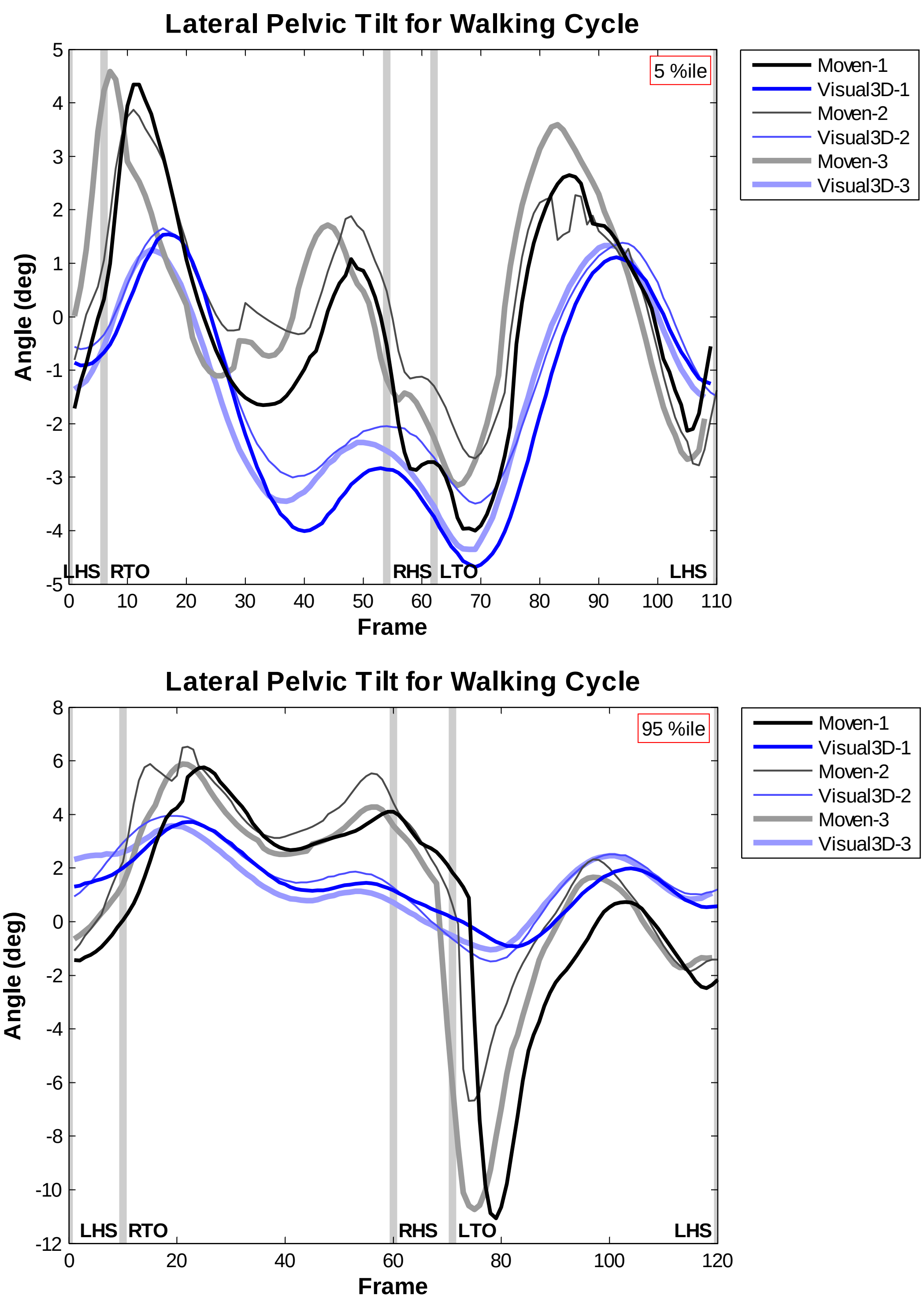


Figure 7 – Lateral pelvic tilt gait determinant for Visual 3D and Moven (beginning, middle, end).

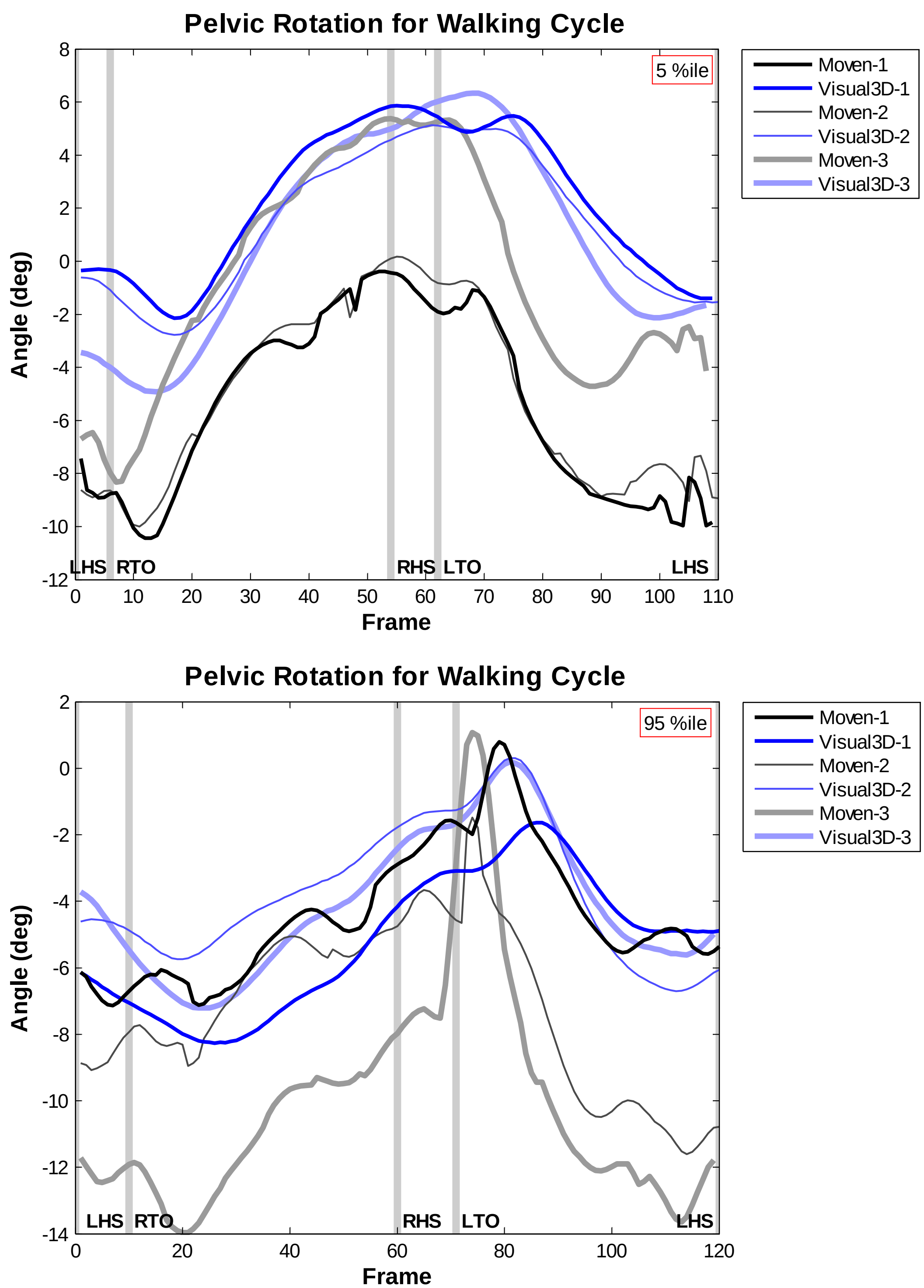


Figure 8 – Pelvic rotation gait determinant for Visual 3D and Moven (beginning, middle, end).

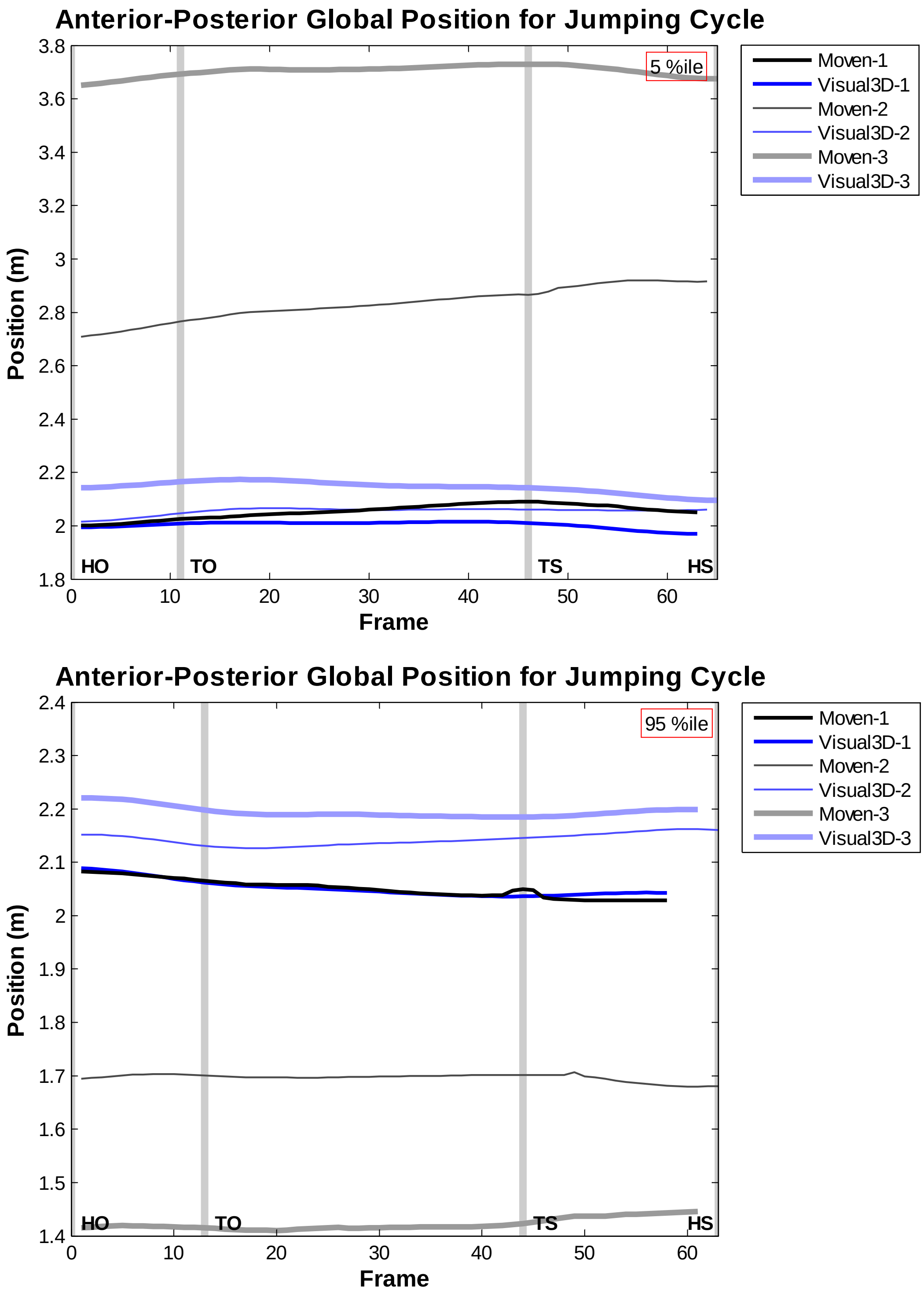


Figure 9 – Anterior-Posterior global position for Visual 3D and Moven (1-beginning, 2-middle, 3-end).

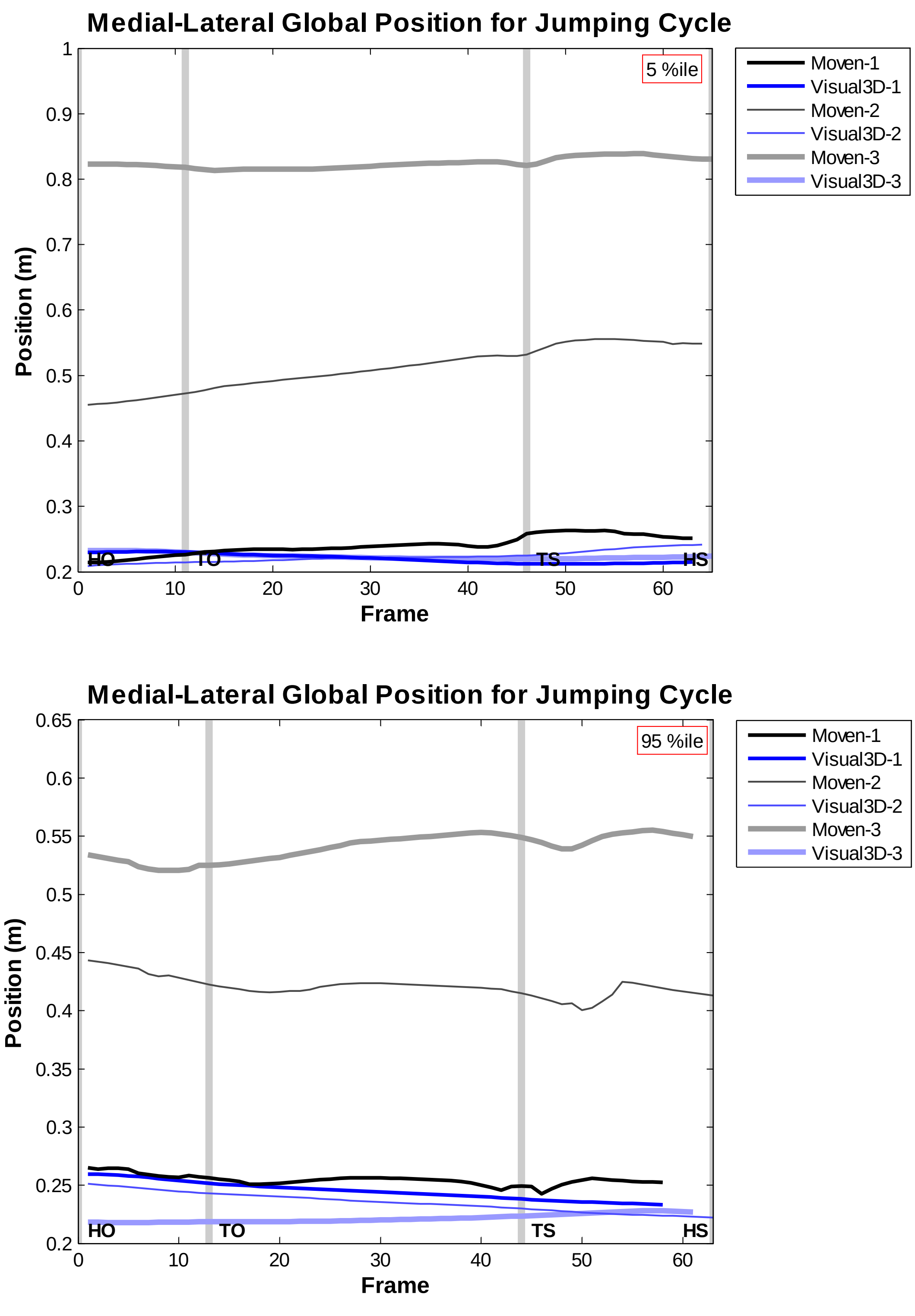


Figure 10 – Medial-Lateral global position for Visual 3D and Moven (1-beginning, 2-middle, 3-end).

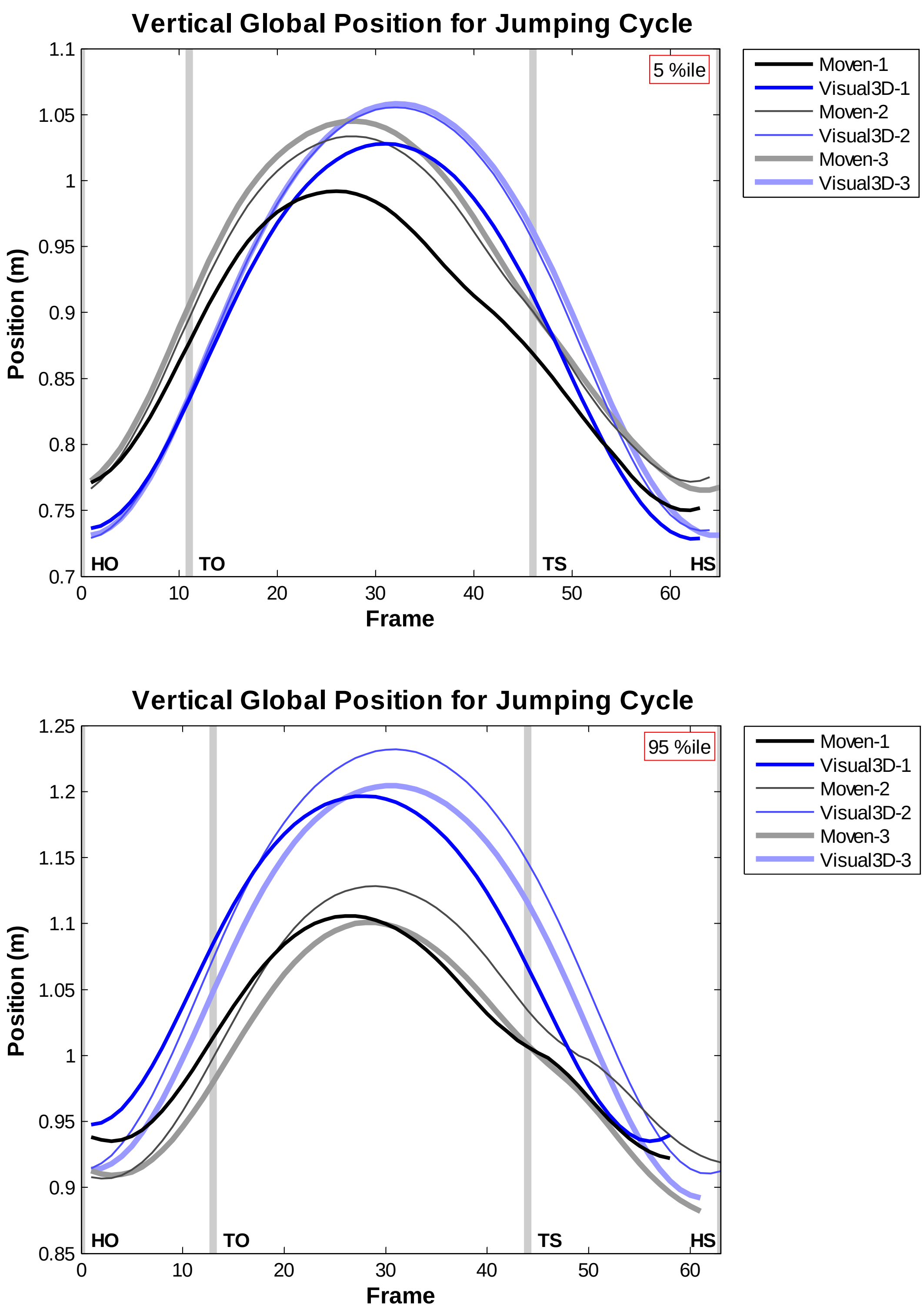
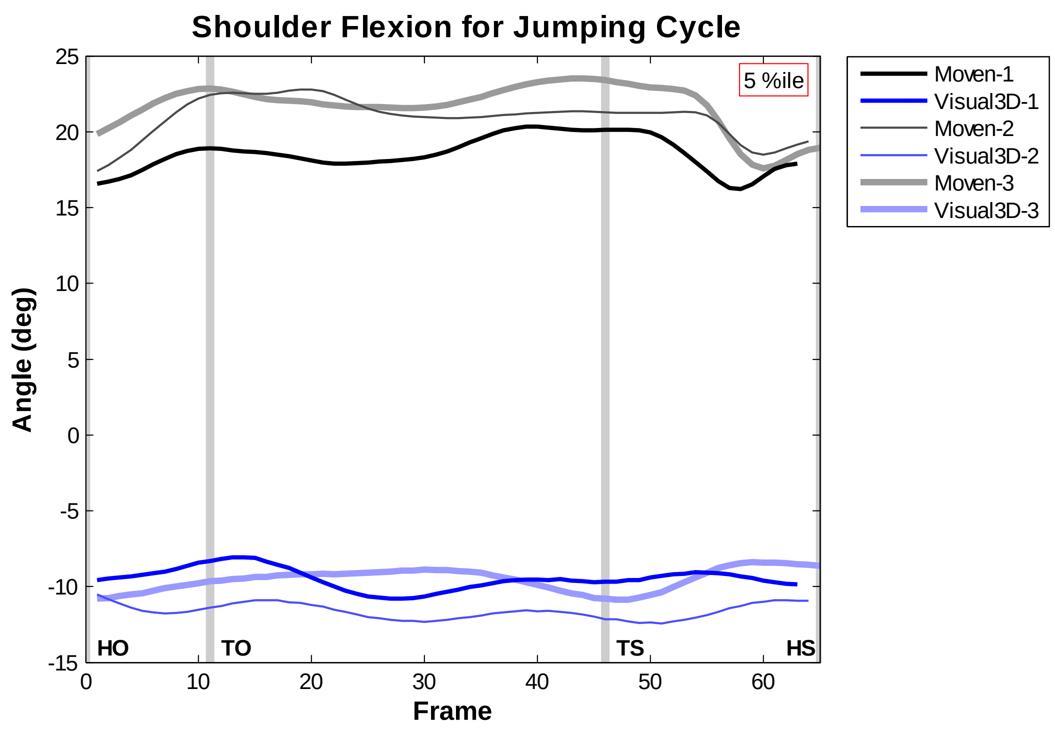


Figure 11 – Vertical global position for Visual 3D and Moven (1-beginning, 2-middle, 3-end).



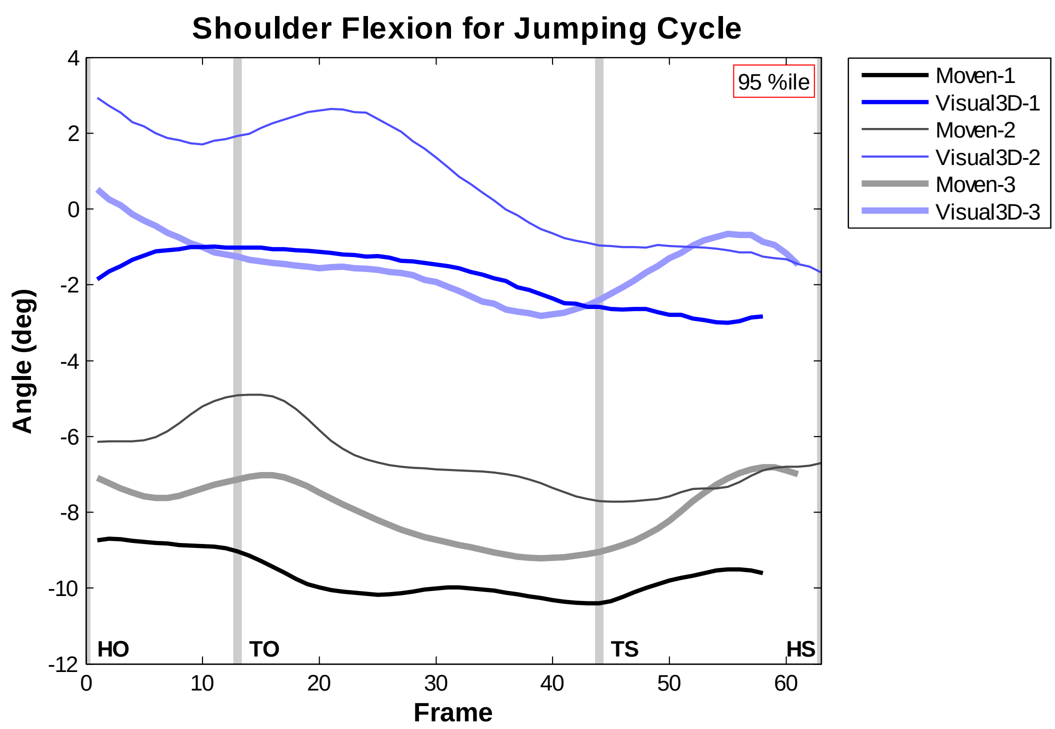


Figure 12 – Shoulder flexion determinant for Visual 3D and Moven (1-beginning, 2-middle, 3-end).

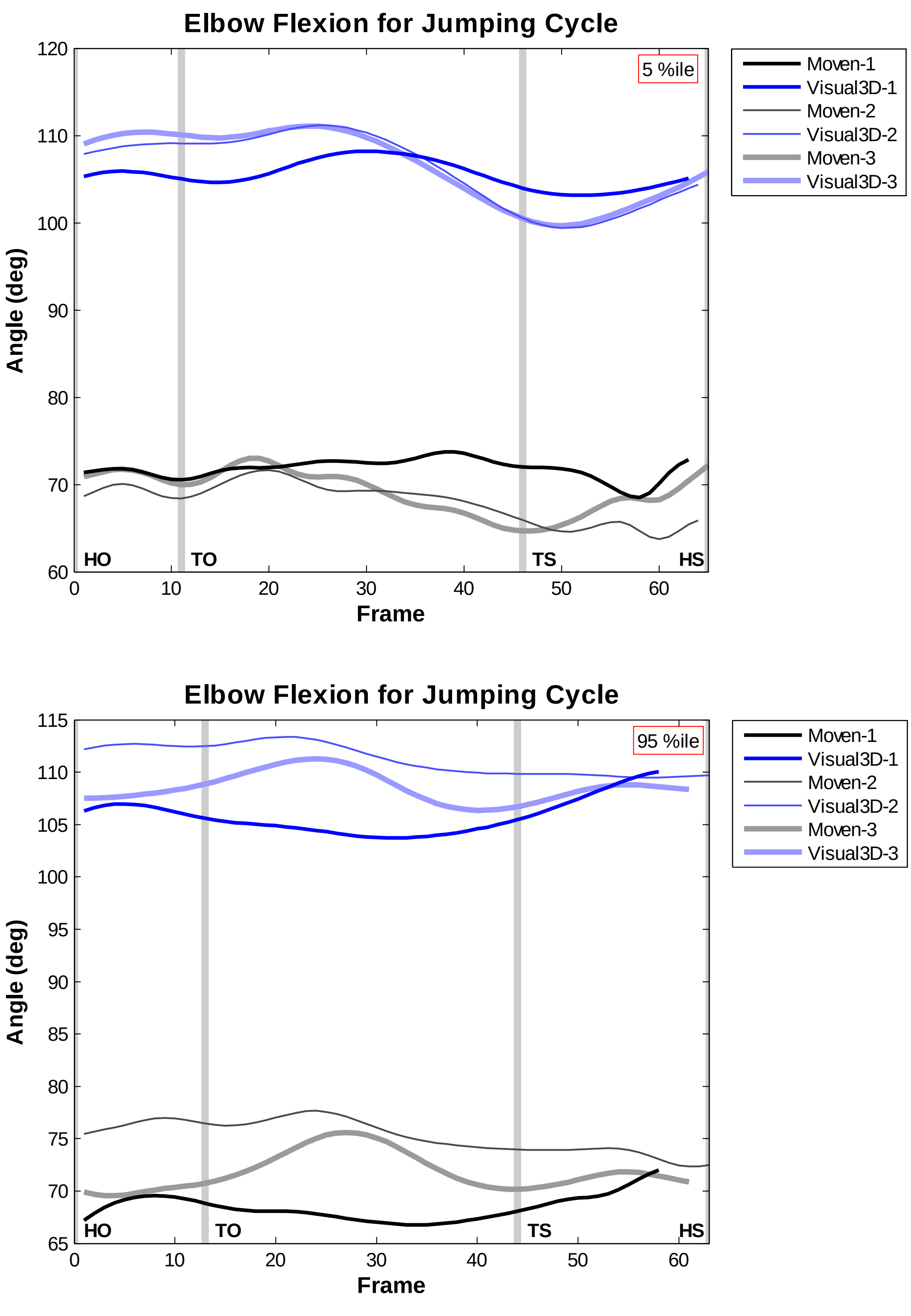


Figure 13 – Elbow flexion determinant for Visual 3D and Moven (1-beginning, 2-middle, 3-end).

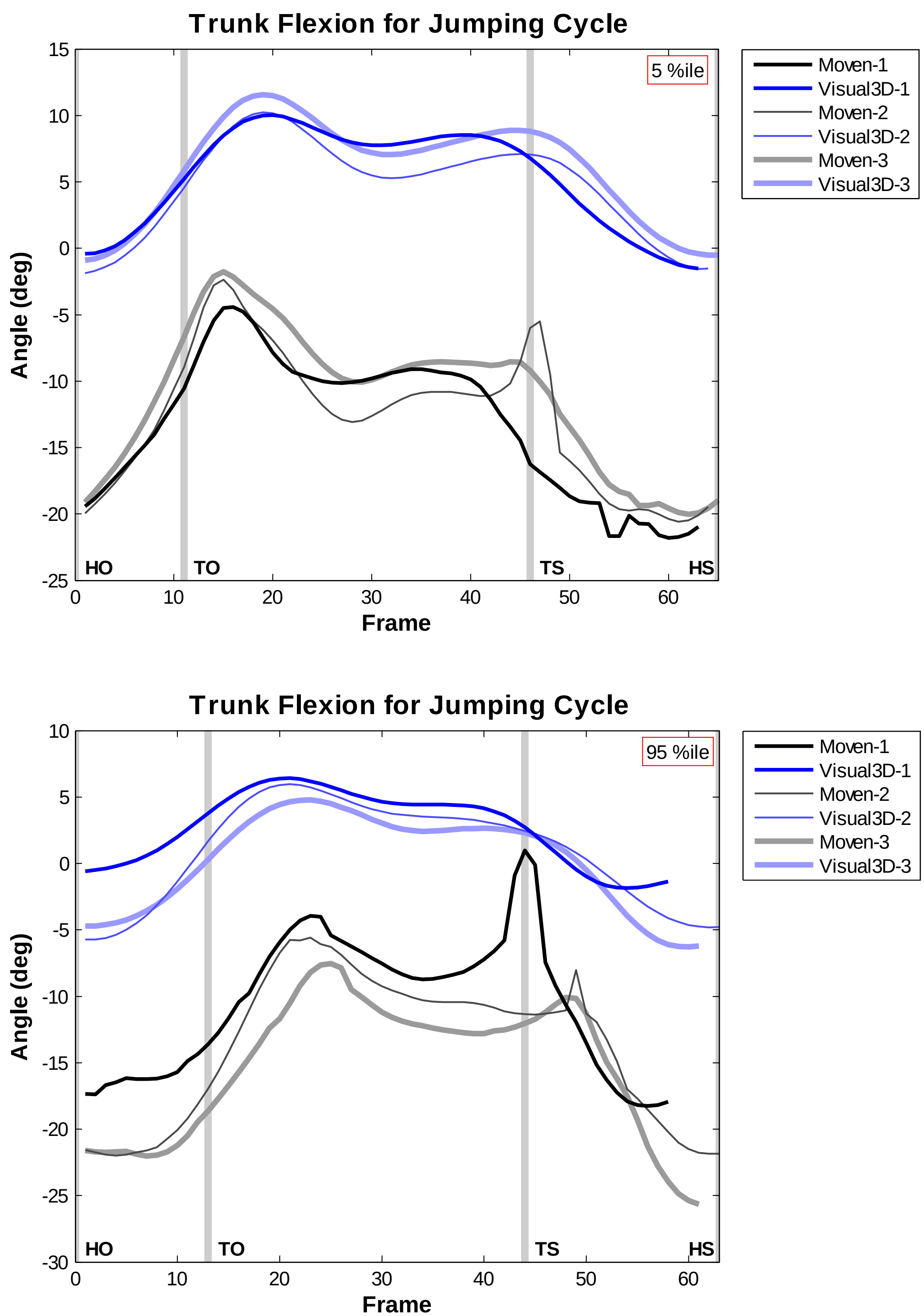


Figure 14 – Trunk flexion determinant for Visual 3D and Moven (1-beginning, 2-middle, 3-end).

*Note – Moven showed a localized spike around impact.

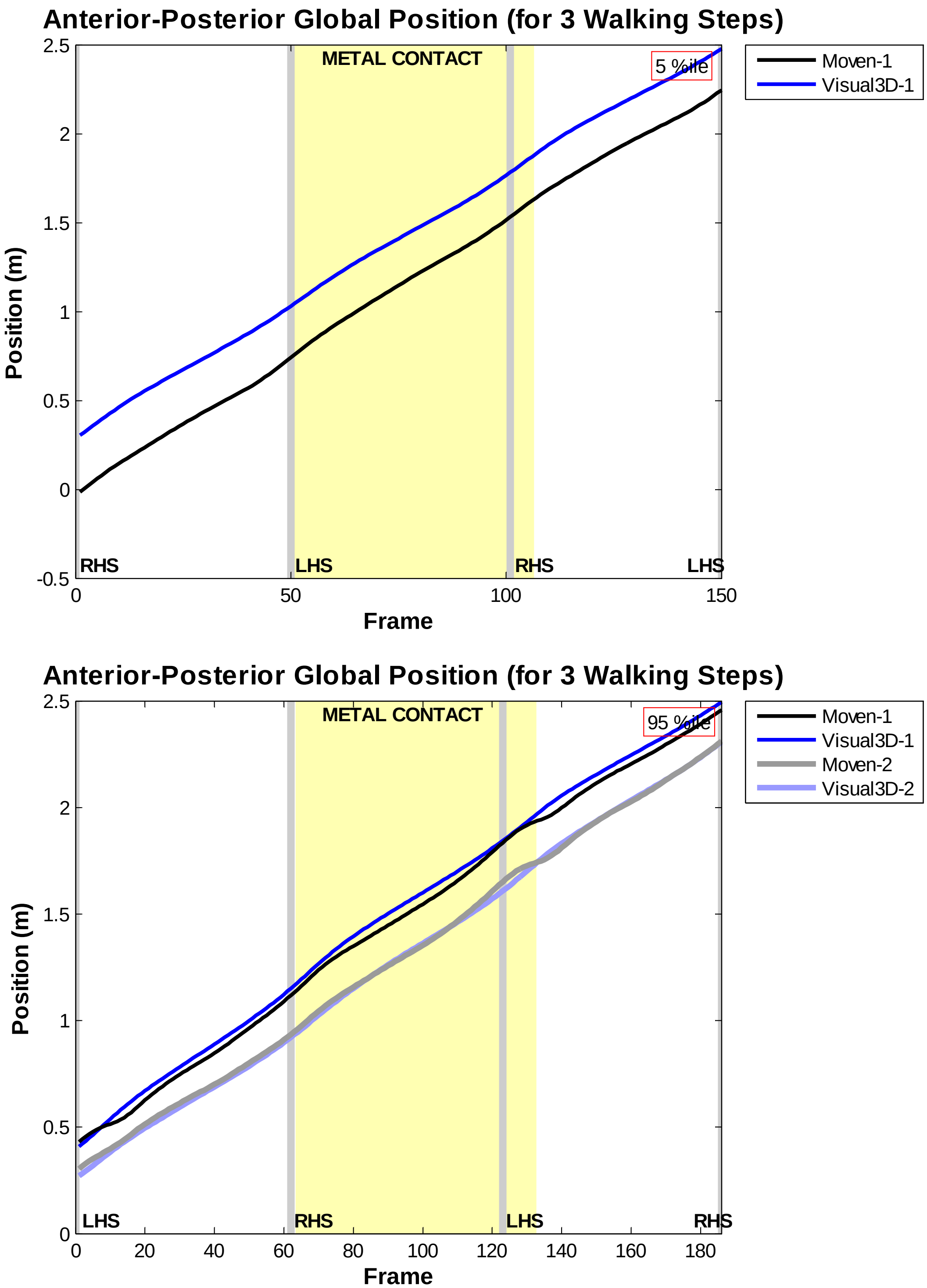


Figure 15 – Anterior-Posterior global position for Visual 3D and Moven.

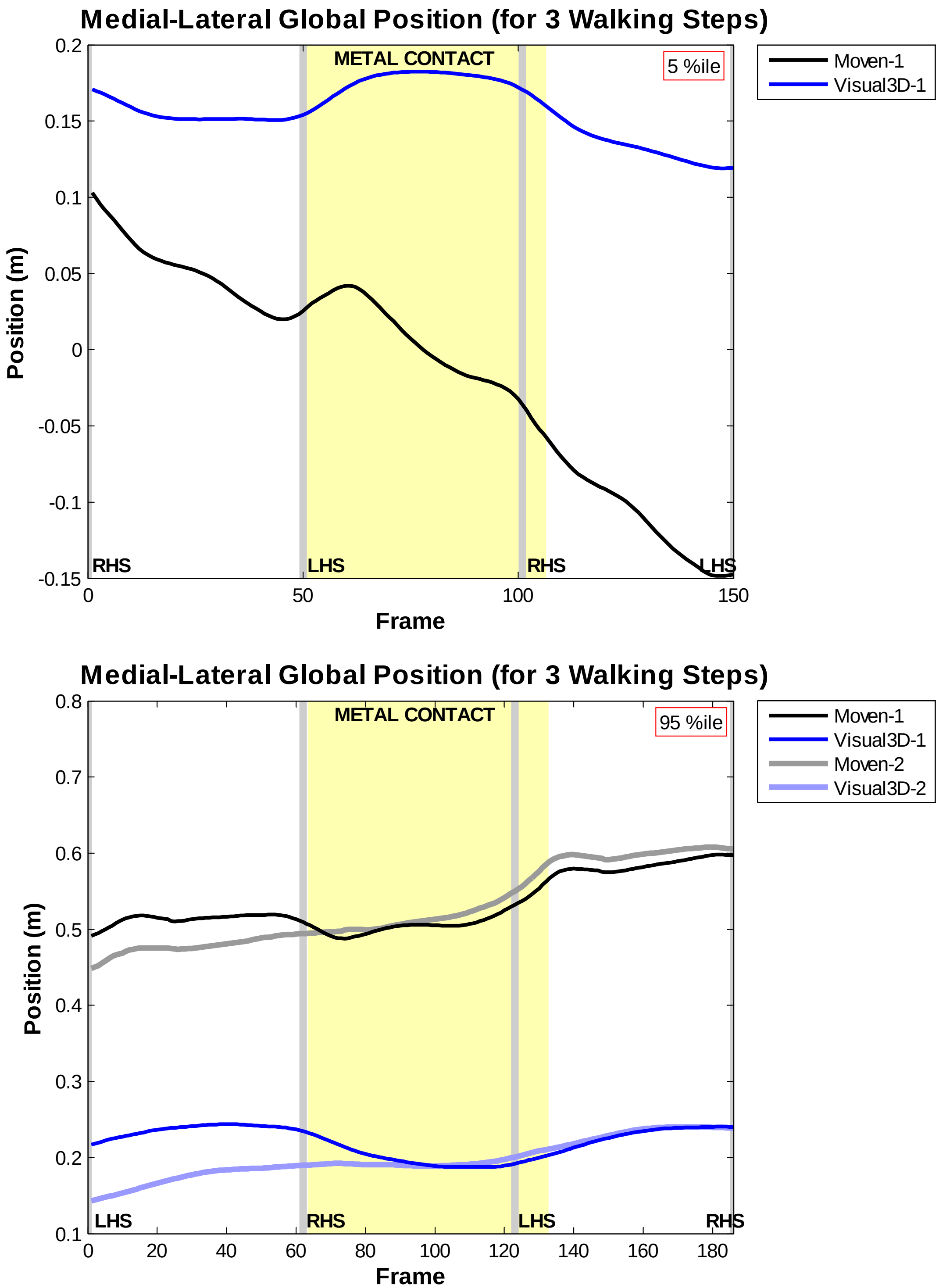


Figure 16 – Medial-Lateral global position for Visual 3D and Moven.

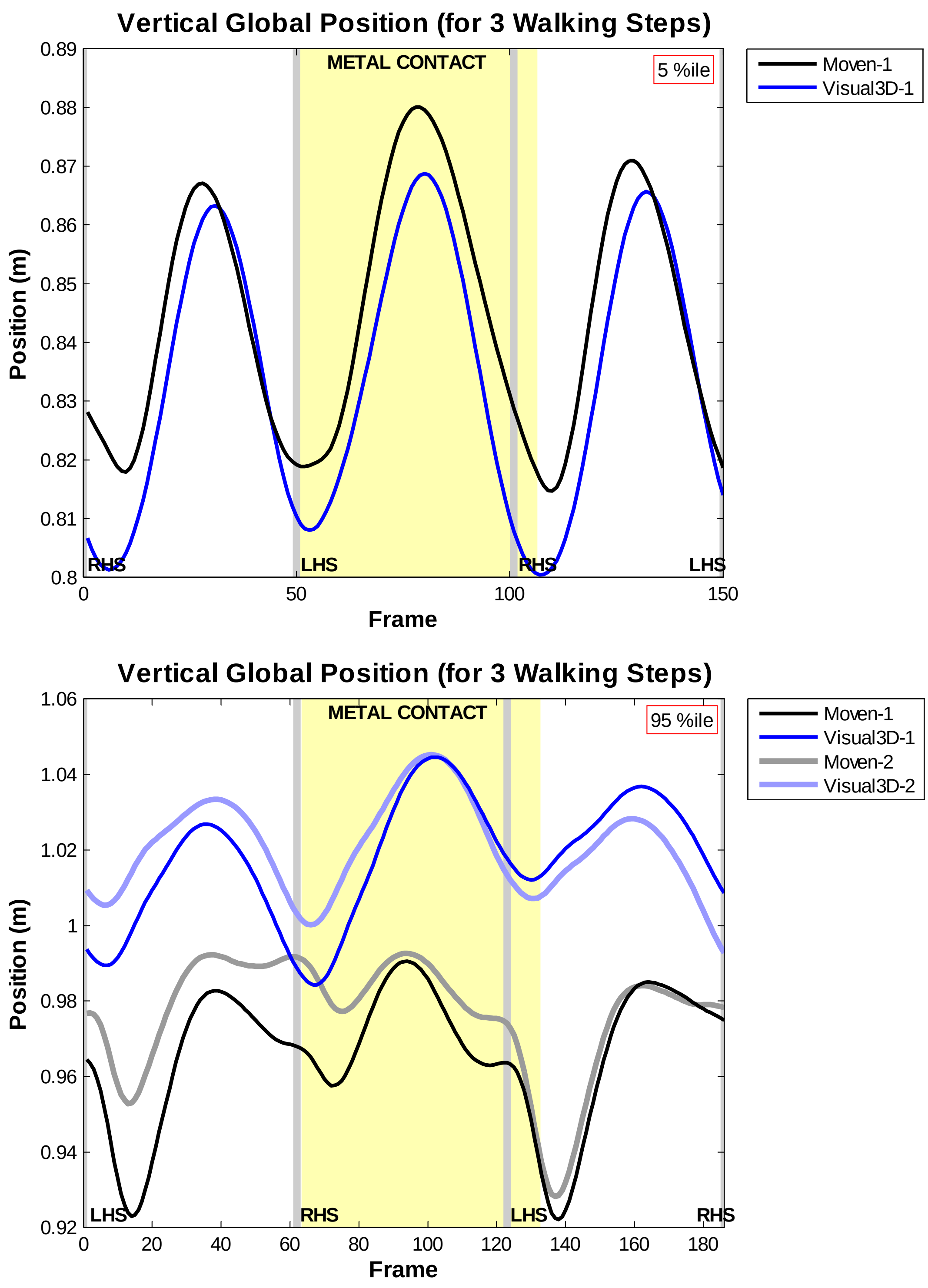


Figure 17 – Vertical global position for Visual 3D and Moven.

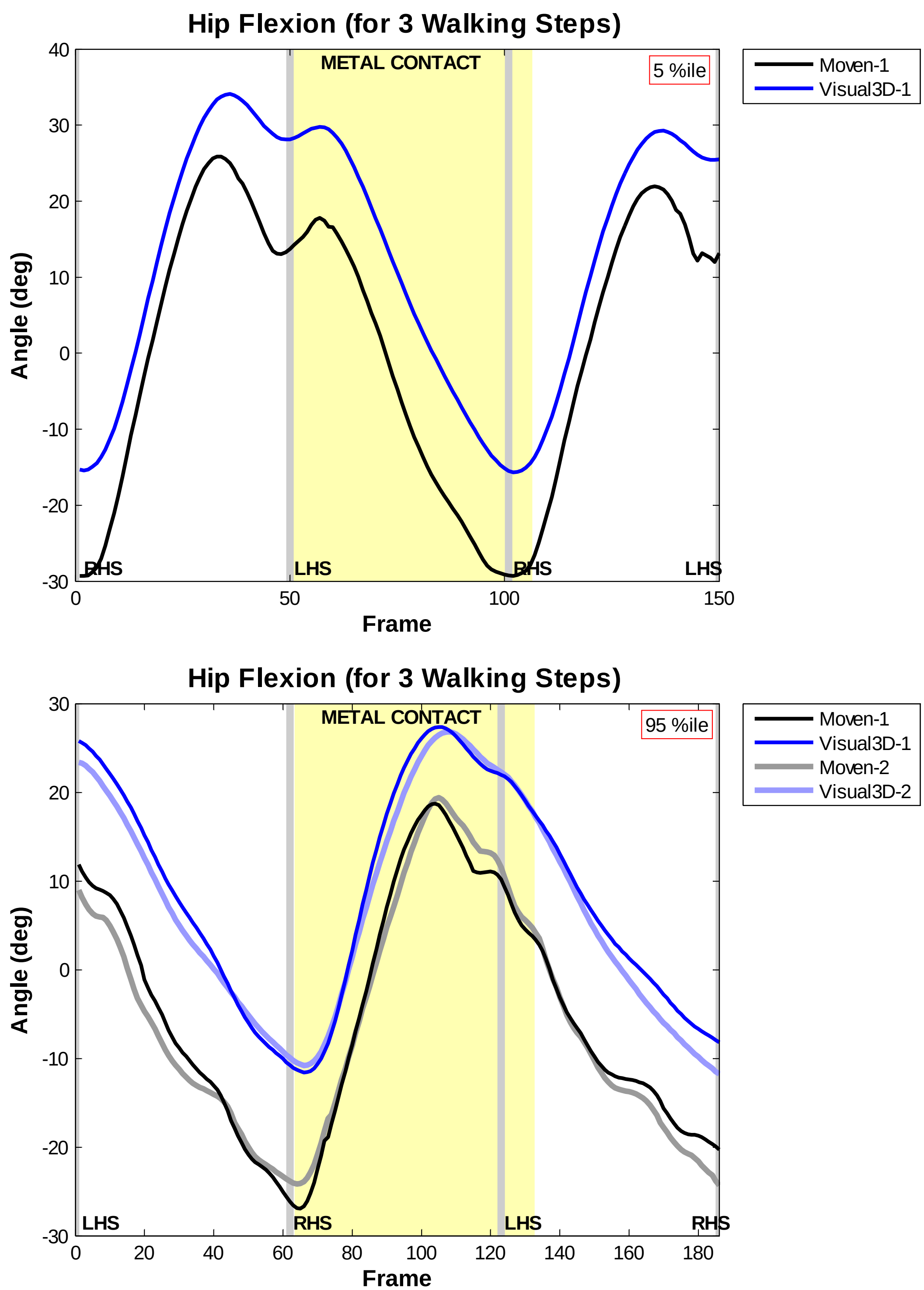


Figure18 – Hip flexion determinant for Visual 3D and Moven.

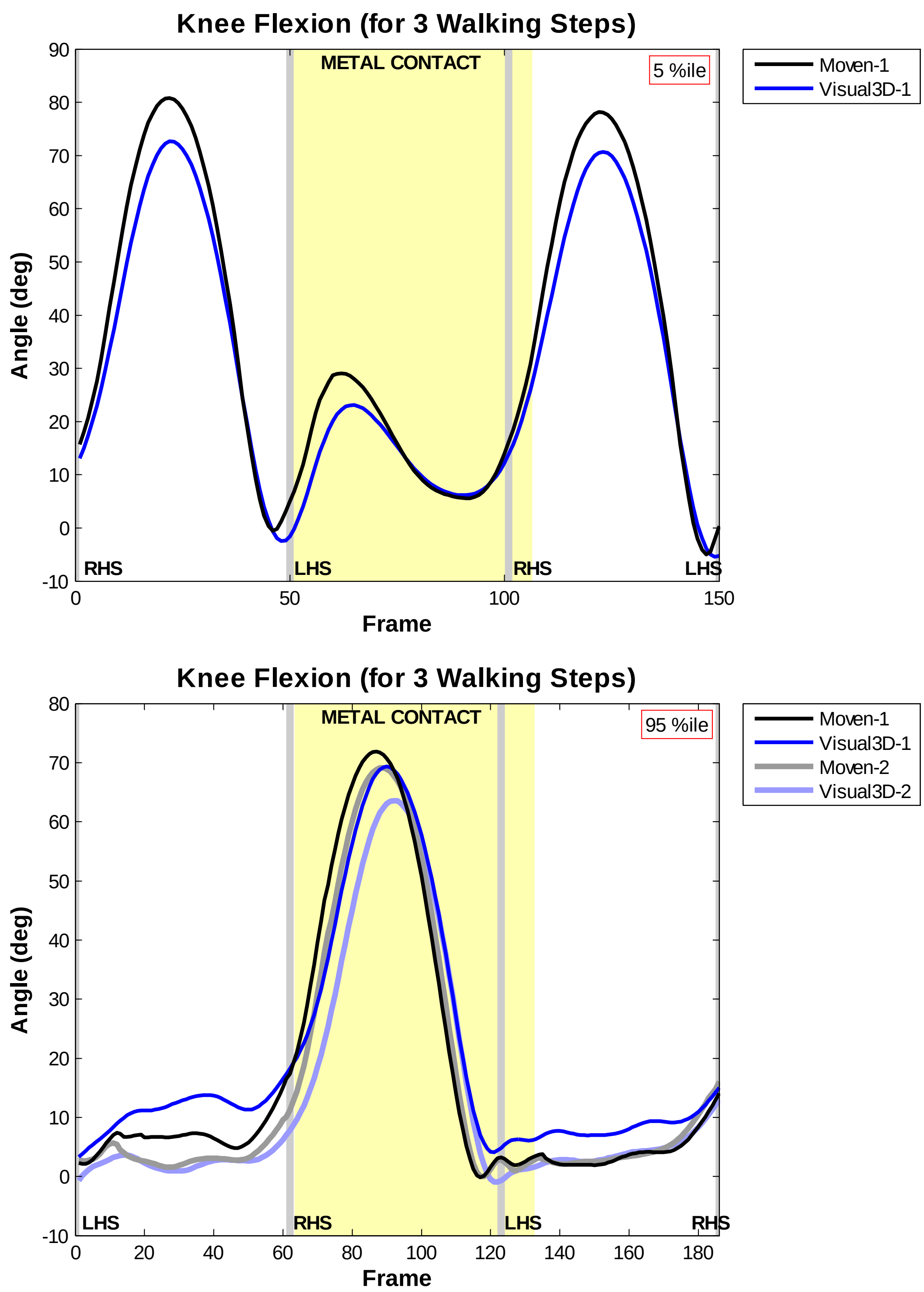


Figure 19 – Knee gait determinant for Visual 3D and Moven.

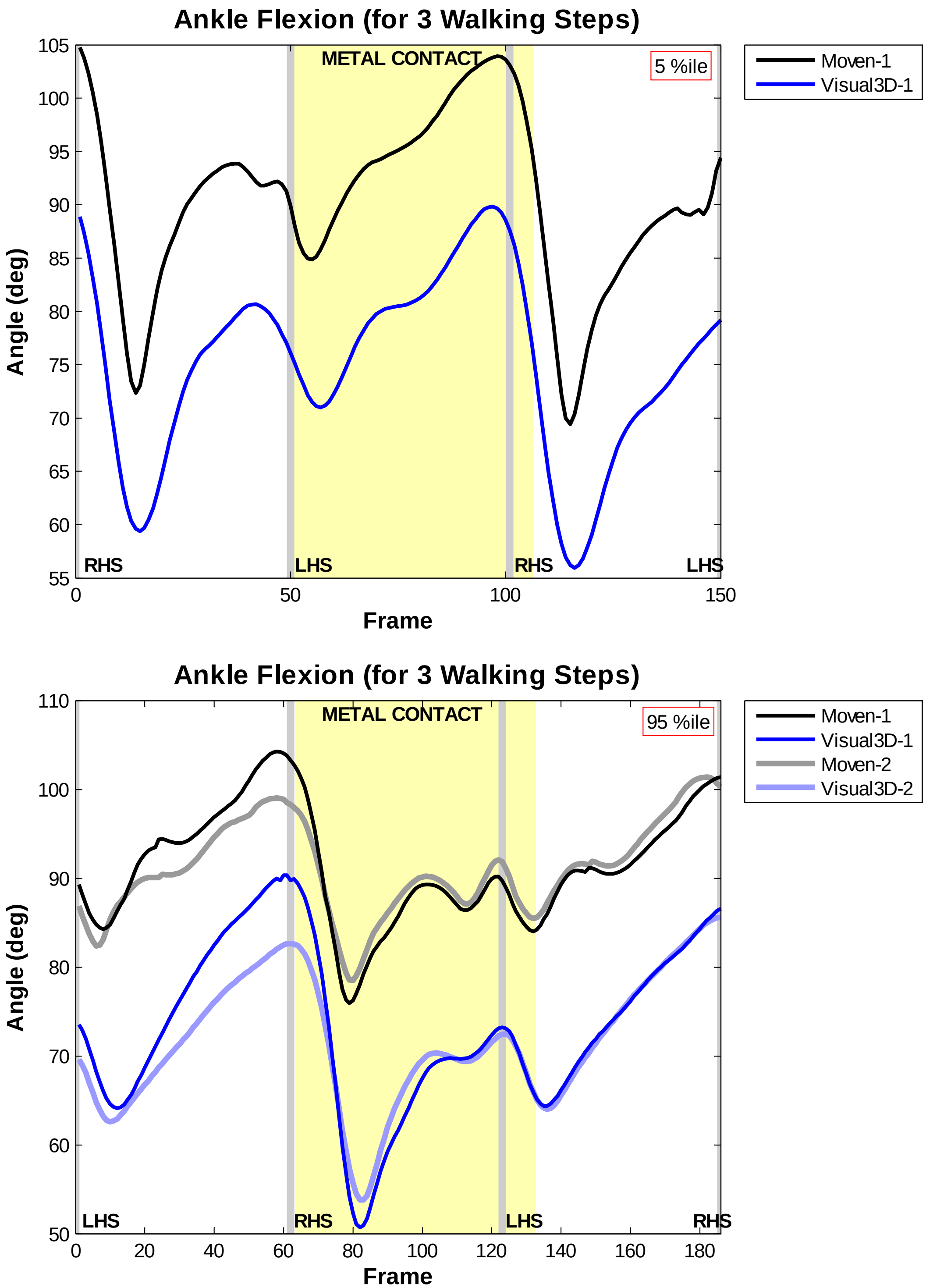


Figure 20 – Ankle gait determinant for Visual 3D and Moven.

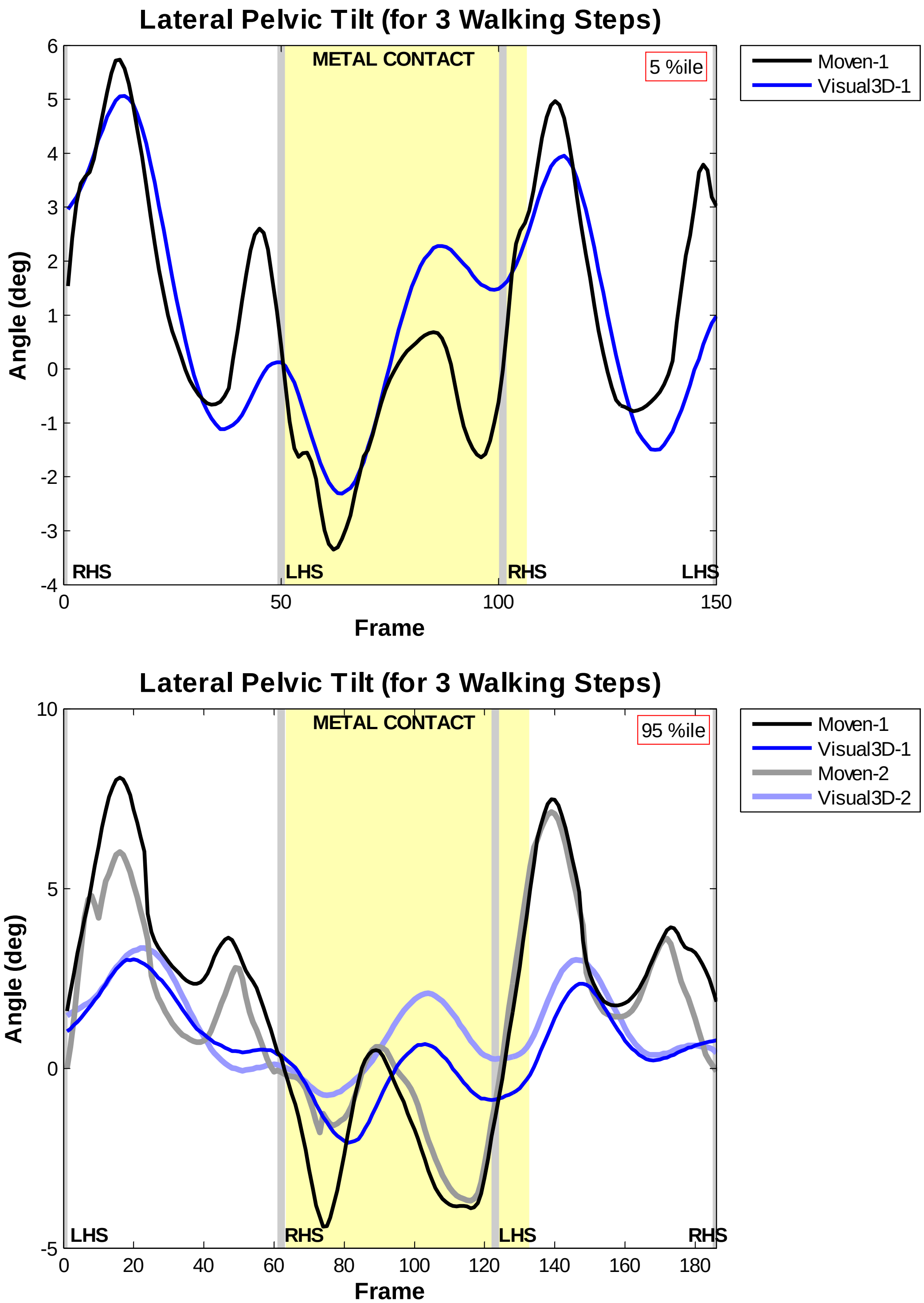


Figure 21 – Lateral pelvic tilt gait determinant for Visual 3D and Moven.

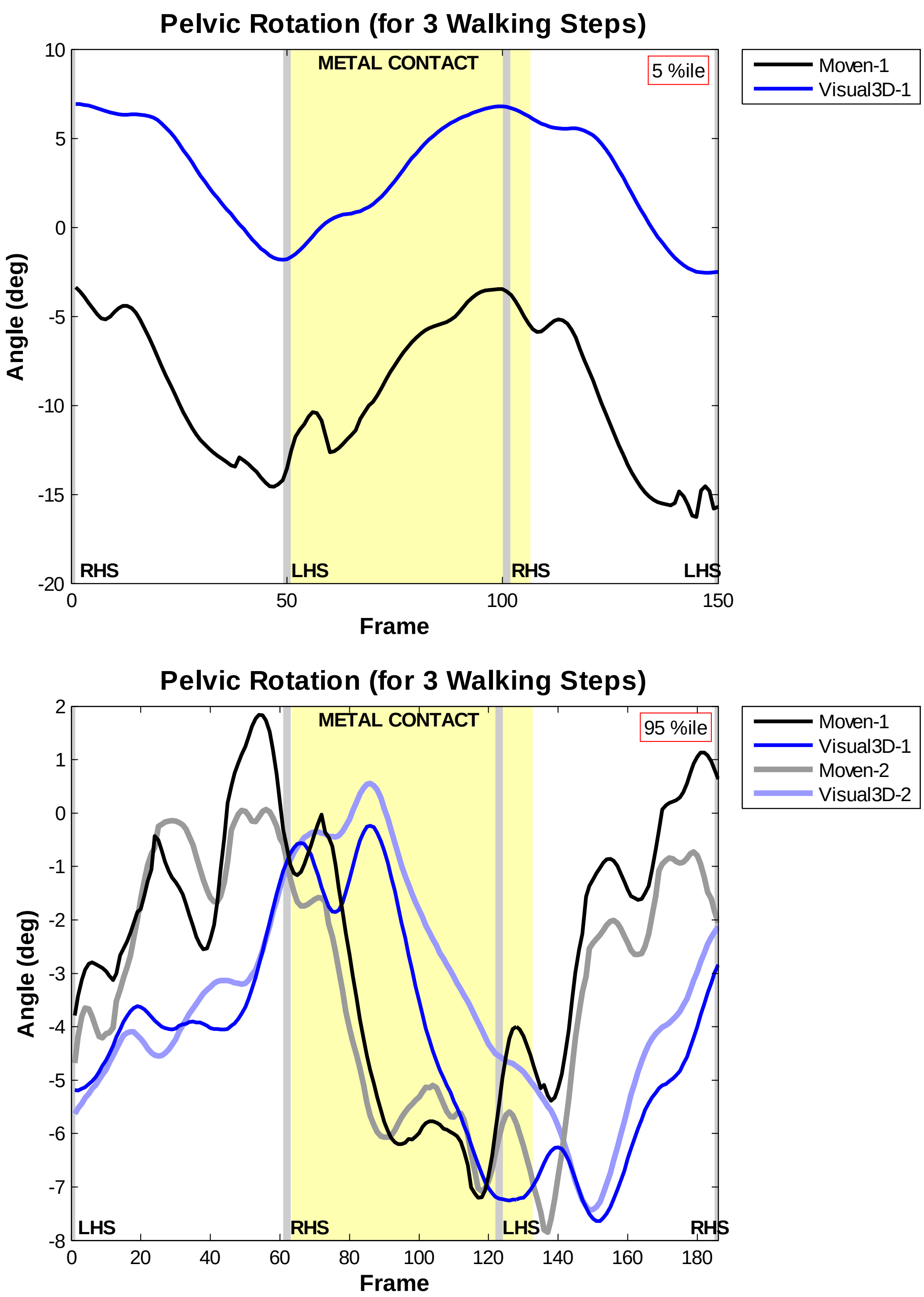


Figure 22 – Pelvic rotation gait determinant for Visual 3D and Moven.

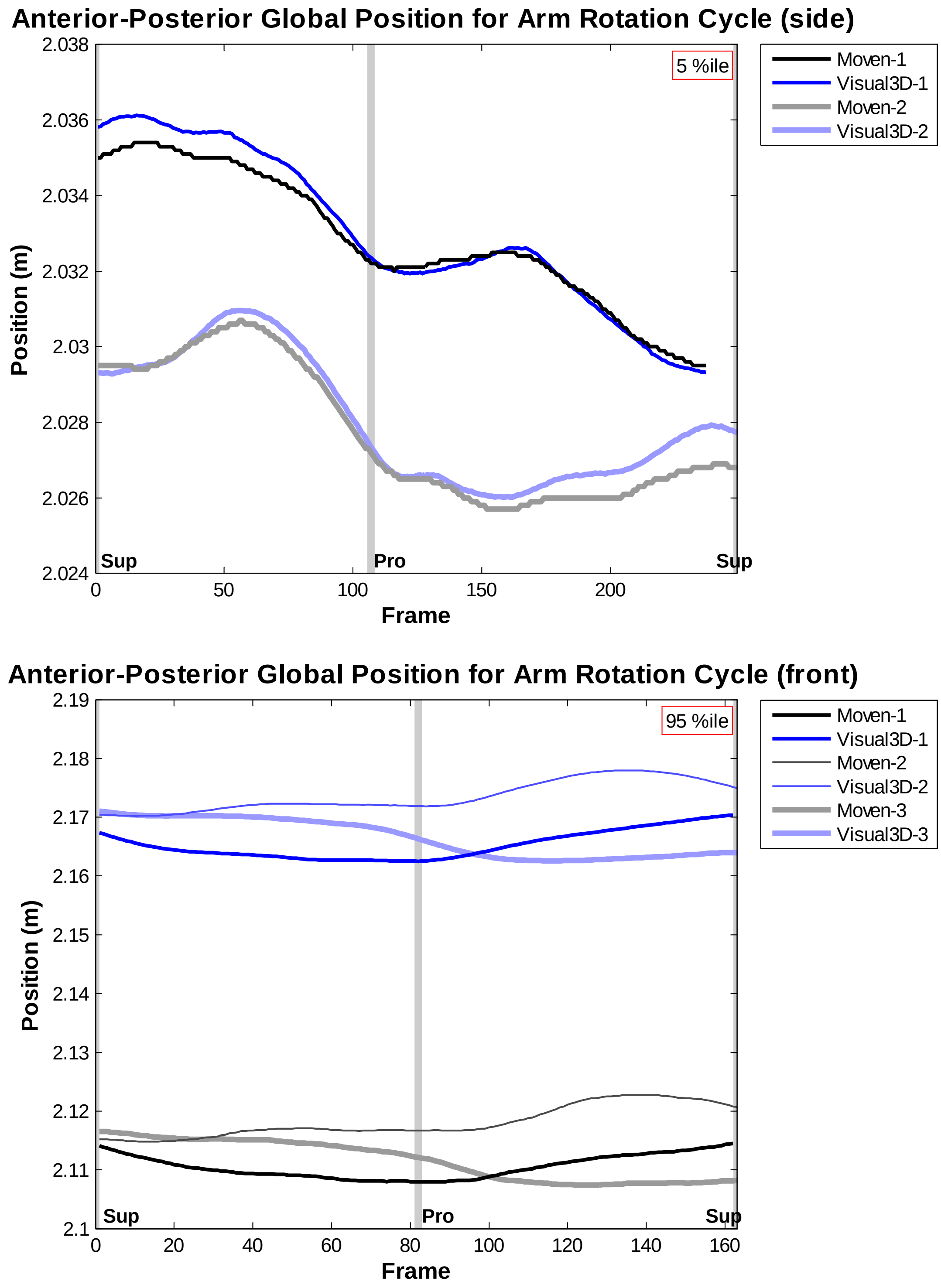
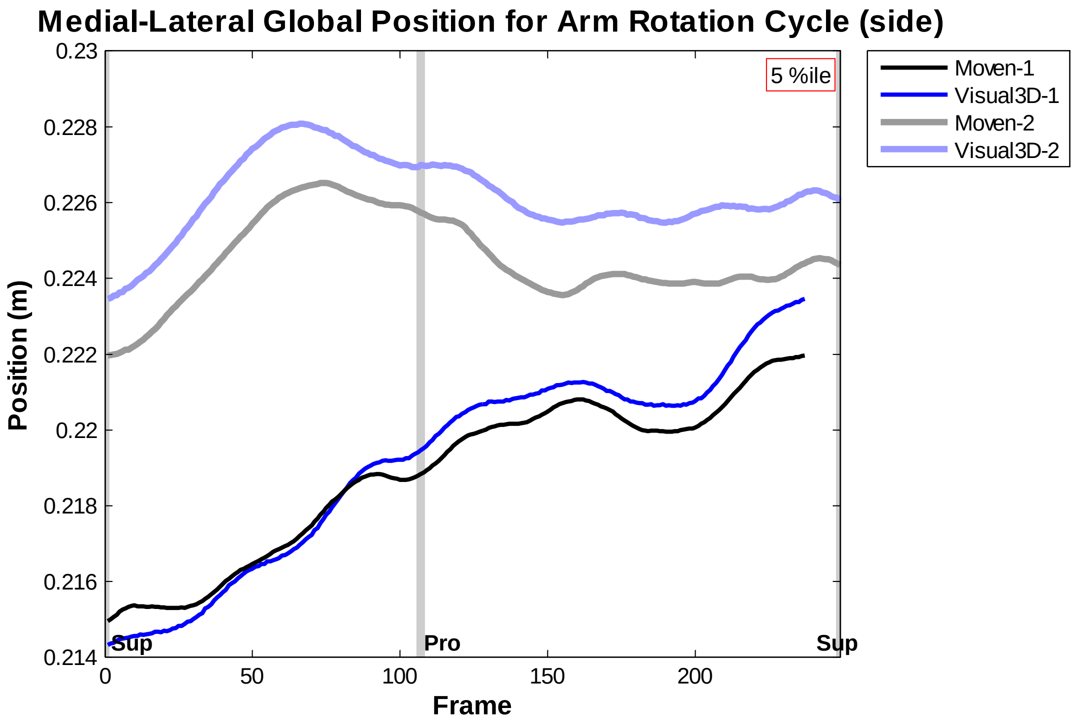


Figure 23 – Anterior-Posterior global position for Visual 3D and Moven (1-beginning, 2-middle, 3-end).



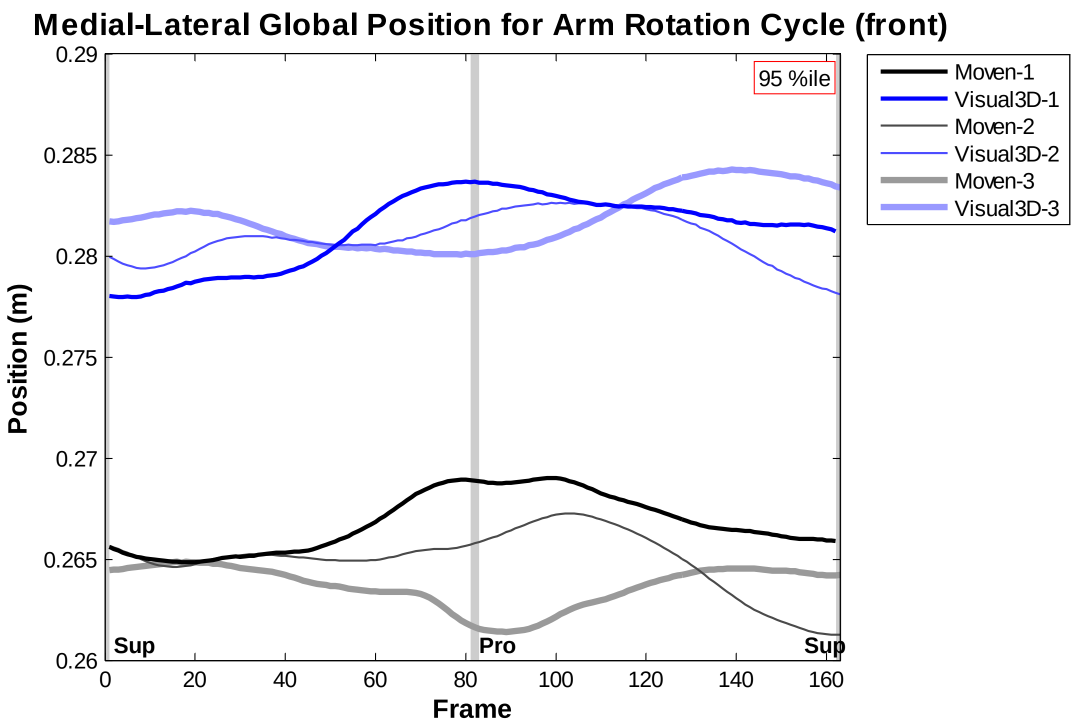
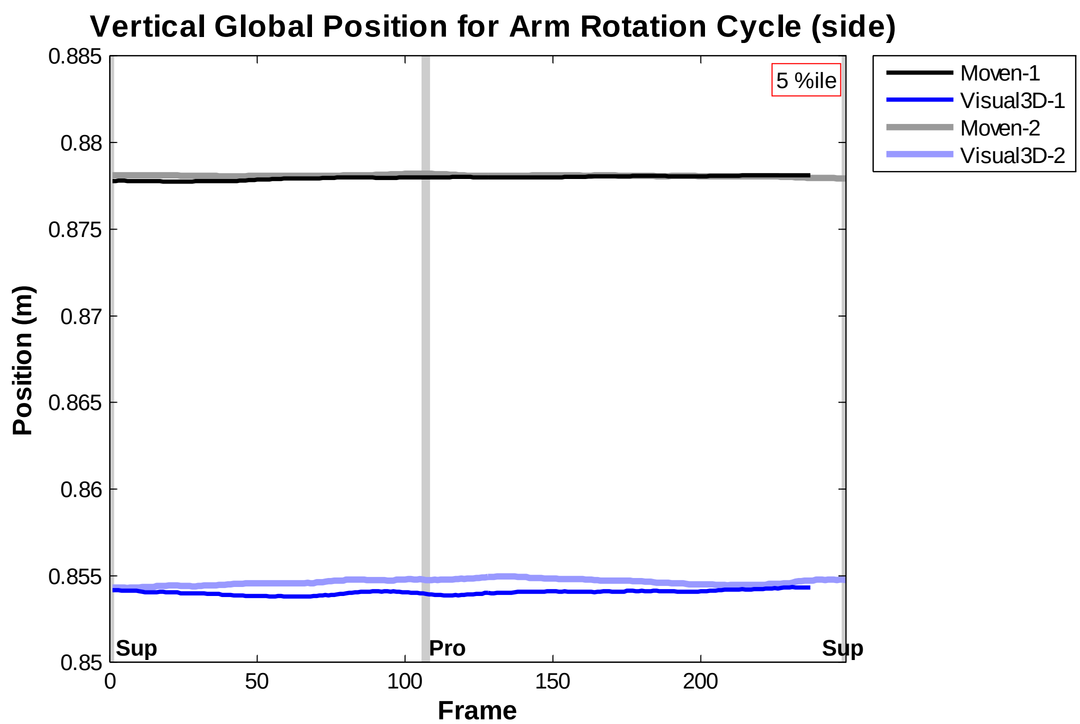


Figure 24 – Medial-Lateral global position for Visual 3D and Moven (1-beginning, 2-middle, 3-end).



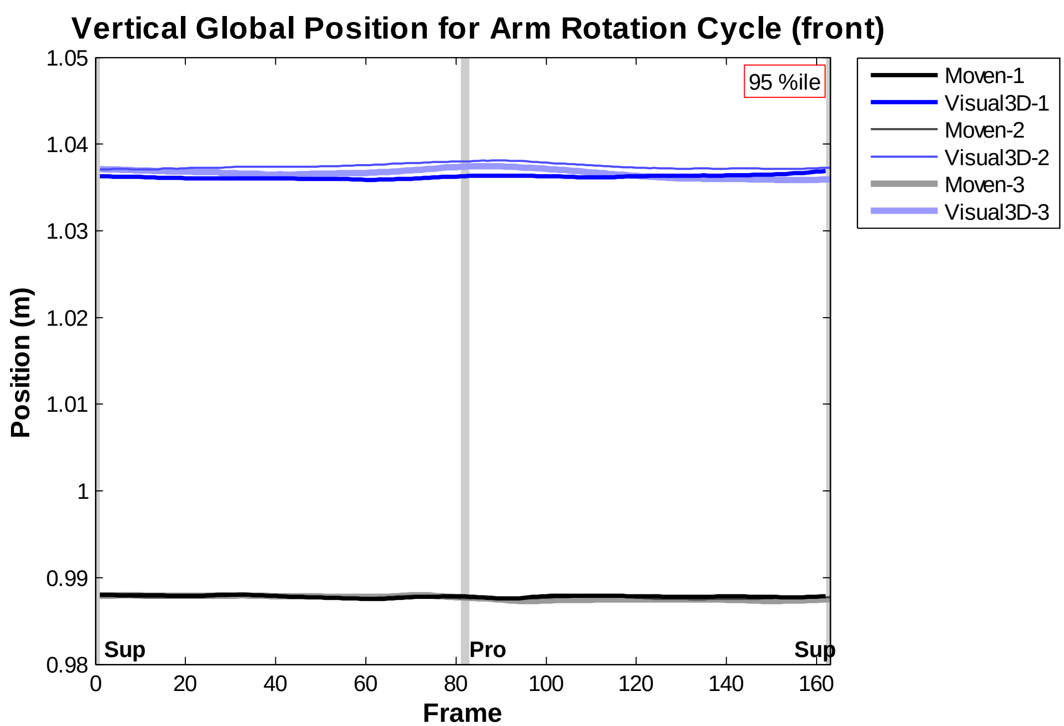


Figure 25– Vertical global position for Visual 3D and Moven (1-beginning, 2-middle, 3-end).

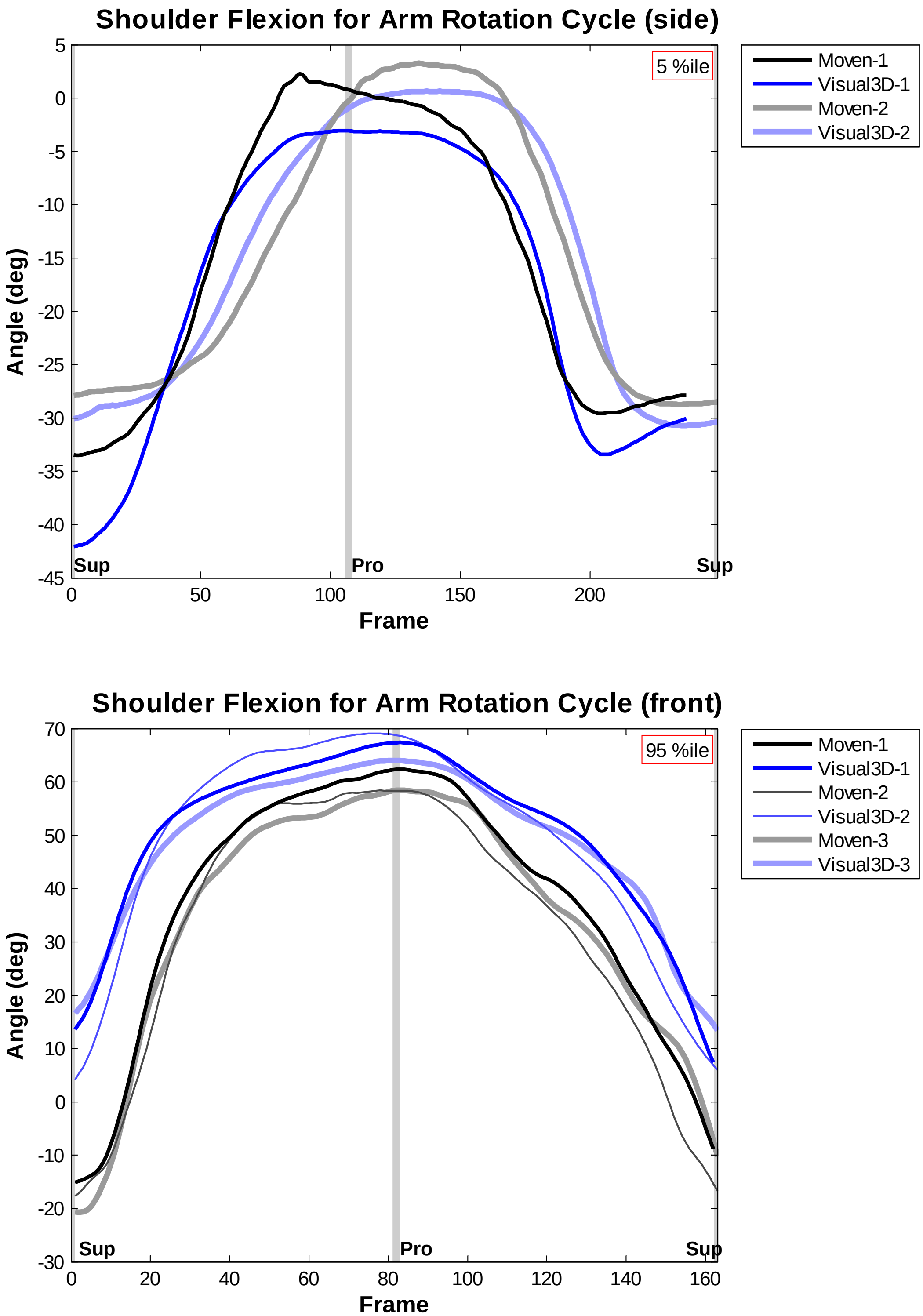


Figure 26 – Shoulder flexion determinant for Visual 3D and Moven (1-beginning, 2-middle, 3-end).

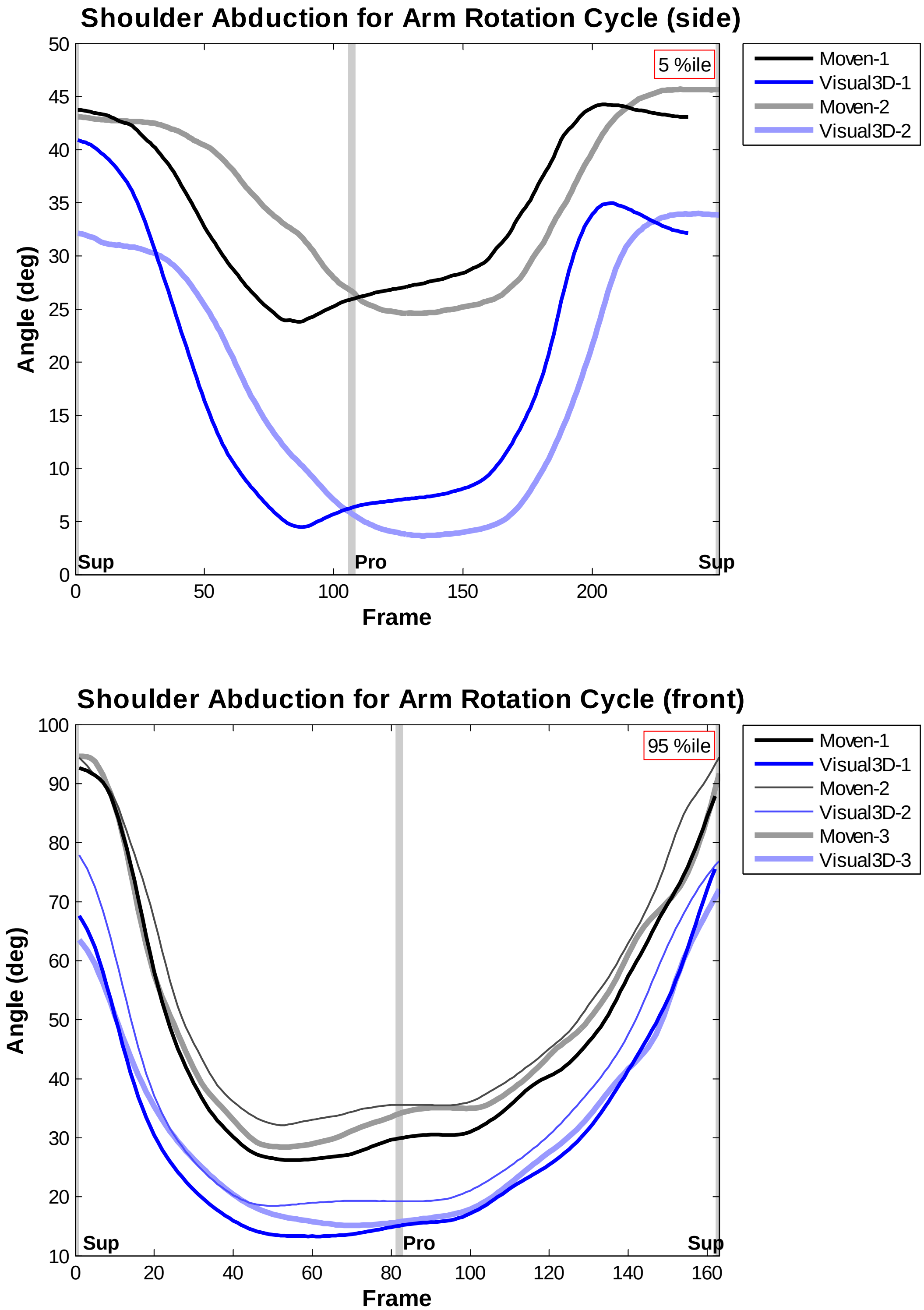


Figure 27 – Shoulder abduction determinant for Visual 3D and Moven (1-beginning, 2-middle, 3-end).

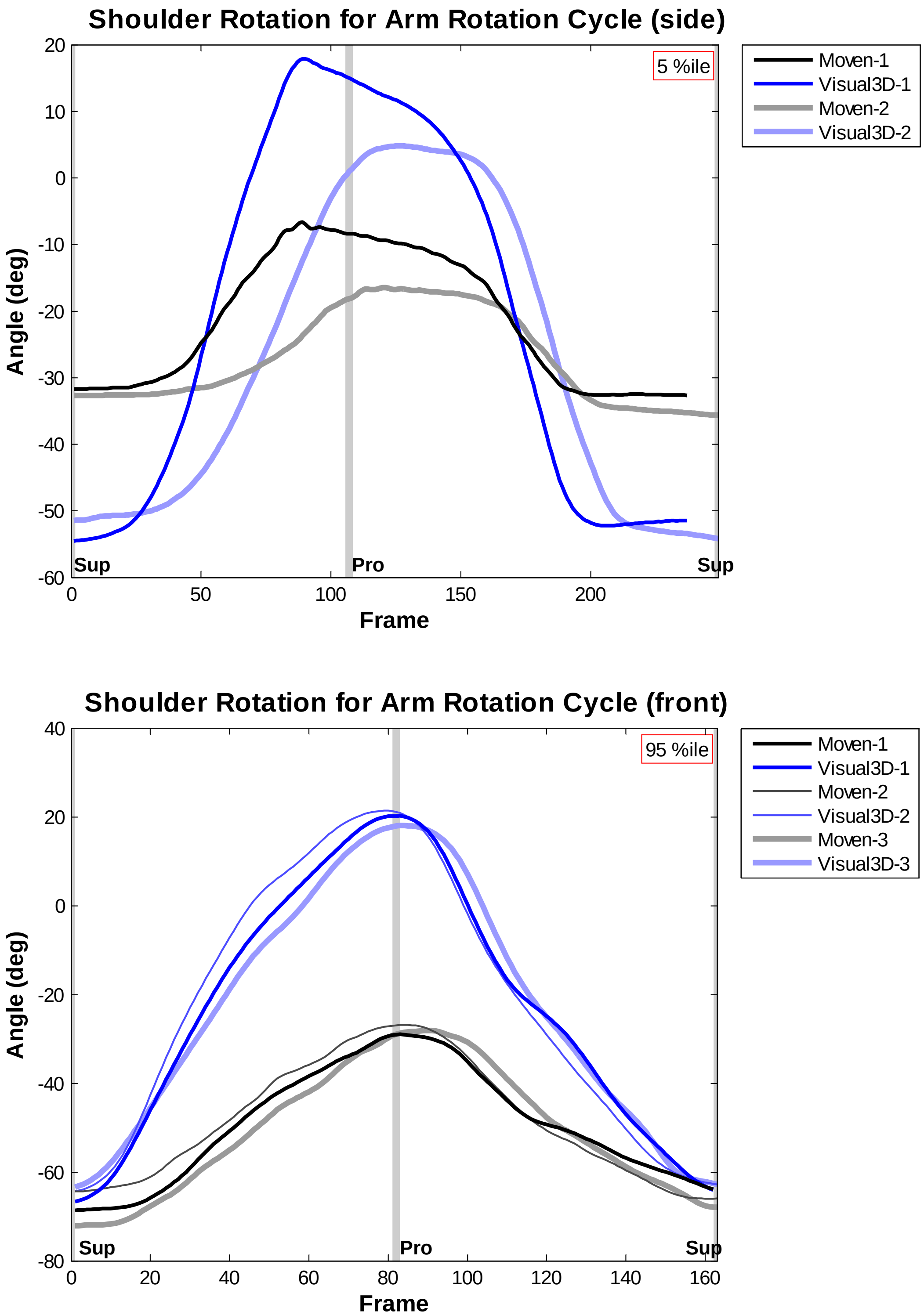
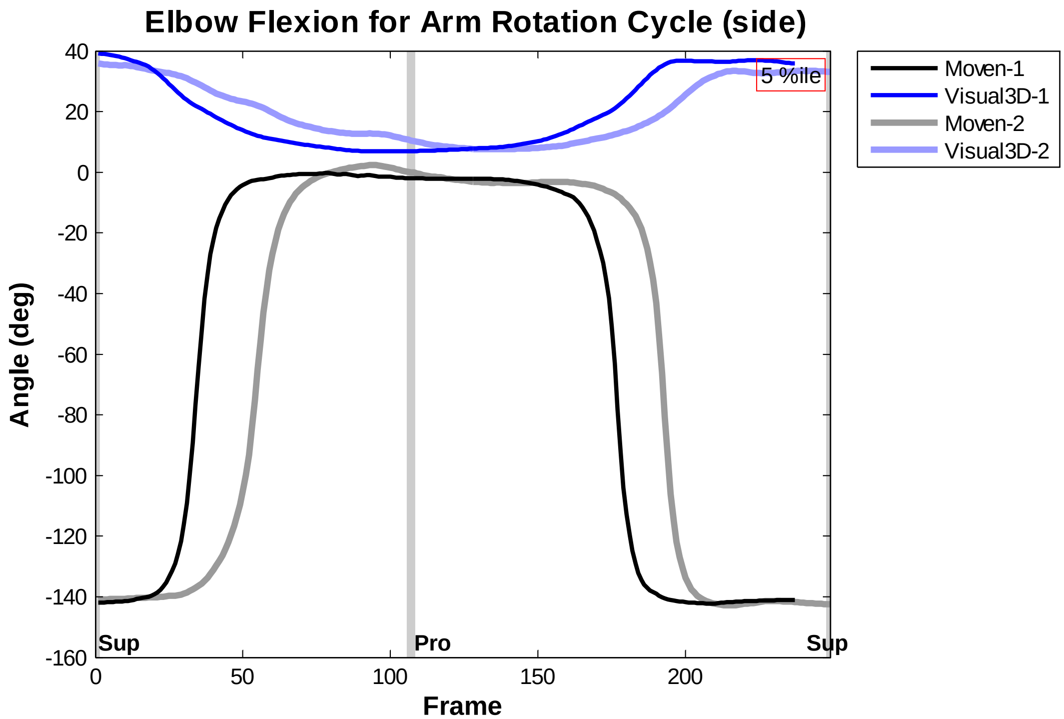


Figure 28 – Shoulder rotation determinant for Visual 3D and Moven (1-beginning, 2-middle, 3-end).



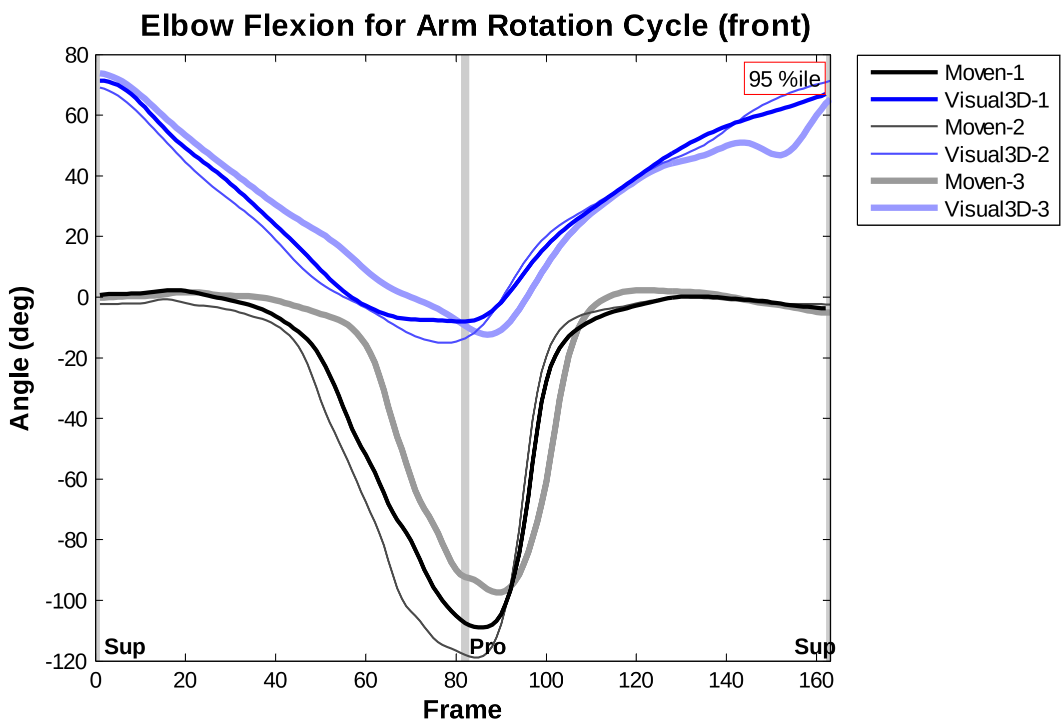


Figure 29 – Elbow flexion determinant for Visual 3D and Moven (1-beginning, 2-middle, 3-end).

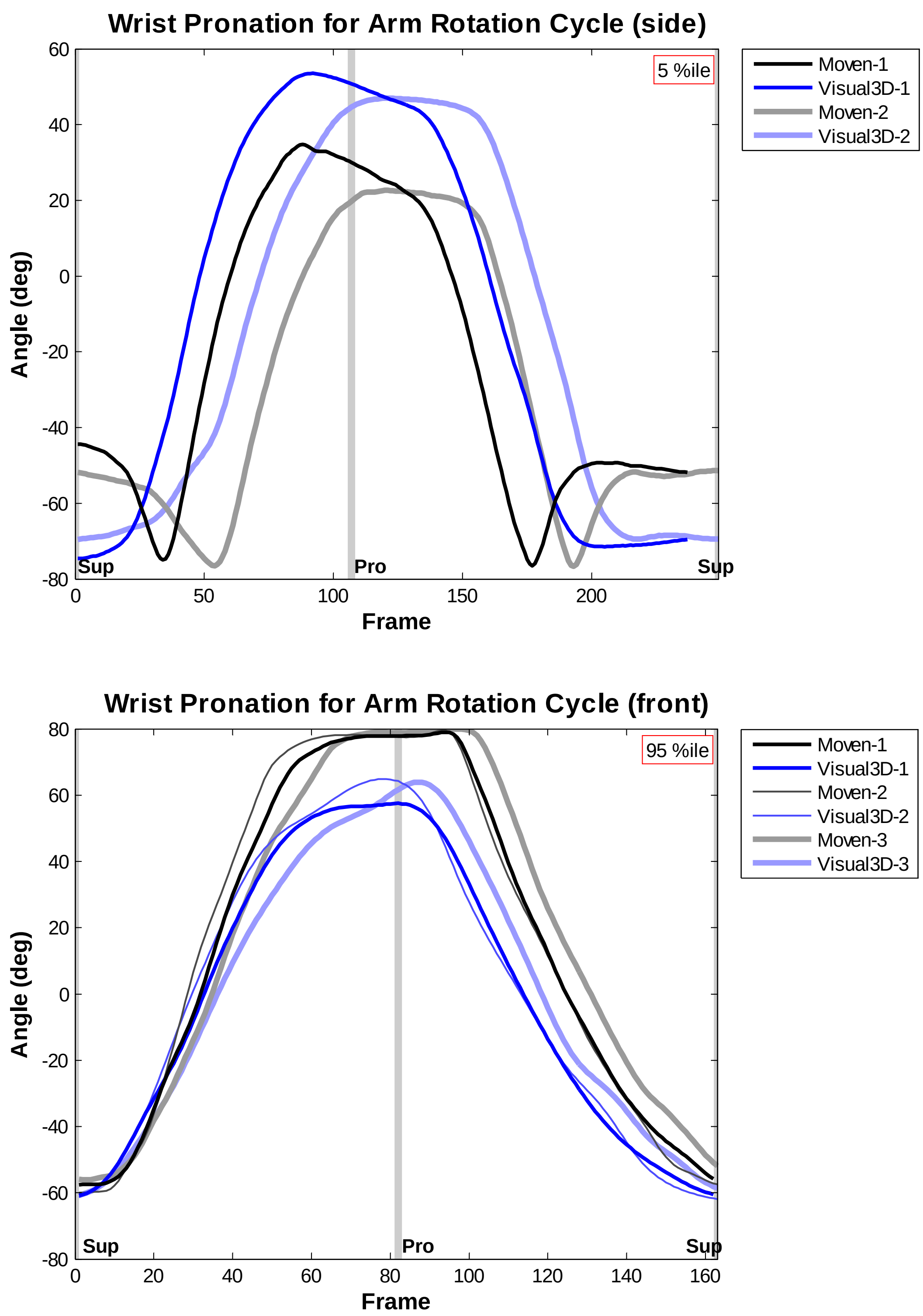


Figure 30 – Wrist pronation determinant for Visual 3D and Moven (1-beginning, 2-middle, 3-end).