A study on the precision of bike tracking techniques during the 3D motion analysis of cyclists while using free-motion and static indoor trainers

Pablo Callejo[1] & Paula Florez[1]

Abstract— **This study presents the results of a comparison between different approaches of dynamic tracking of the bike while performing a full-body, real-time, 3D motion analysis on cyclists using a free-motion trainer (Fig. 1). The biomechanical analysis was carried out with Cycling 3DMA v. 2019.0, a software package developed by STT Systems (https://www.stt-systems.com/) and based on passive marker tracking algorithms and a robust kinematics module with various data visualization options. The free-motion trainer selected was the Oreka O2 Trainer (https://www.orekatraining.com).**

I. INTRODUCTION

Being able to accurately locate the bike during a bike fitting session is crucial for the validity of certain output parameters remarkably those that use the bike as a reference, such as the lateral position of body landmarks in relation to the bike plane. This is usually less of a problem when working with static trainers, since bike fitting solutions can rely on simple procedures to set a fixed reference plane at the point where the bike is located.

The arrival of indoor trainers that offer cyclists a greater freedom of movement has encouraged bike fitters and sports scientists to wonder whether if it is possible to enhance their bike fitting solutions to track the body motion of the cyclist relative to a freely sliding bike.

II. MARKERSET DEFINITION

In order to accurately compare the different approaches to the tracking of the bike during captures, it was important to establish which markersets were going to be used and the information each of them would provide for the final results. The body tracking remained identical for each approach while three different markersets for bike tracking were used as described in Table I.

The markersets used for body and bike tracking (”Full-body + floor markers”, ”Full-body + bike markers” and ”Only full-body markers”) correspond to biomechanical analysis protocols from the Cycling 3DMA software package by STT Systems, while the bike tracking used for the free-motion trainer (2 bike markers + 1 floor marker) is a variation of the Bike Markers protocol that was used as the ground-truth for the free-motion comparisons.

*This is an internal study and its results are not meant for publication or use outside of the company or its authorized clients.

[1]Motion Capture Division, STT Systems. `www.stt-systems.com` San Sebastian, Spain.

Fig. 1. Cyclist on a free-motion trainer during a 3D motion analysis.

TABLE I
BIKE TRACKING APPROACHES

Markersets	Body Tracking	Bike Tracking
Bike Fitting (Full-body+floor)	20 markers from Fig. 2	Floor markers: 3. Bike markers: 0 (Markers 21-23 from Fig. 3)
Bike Fitting (Full-body+bike)	20 markers from Fig. 2	**For the free-motion tests:** Floor markers: 1. Bike markers: 2 (Markers 23-25 from Fig.3) and **for the static trainer tests:** Floor markers: 0. Bike markers: 4 (Markers 26-29 from Fig.3)
Bike Fitting (Full-body)	20 markers from Fig. 2	Floor markers: 0. Bike markers: 0

A. Bike Fitting (Full-body + floor markers)

This markerset contains the body markers and static markers on the floor to define the bike plane. It was designed with a static trainer in mind, since it assumes an unmoving bike plane throughout the entire capture.

B. Bike Fitting (Full-body + bike markers)

This markerset contains the body markers and 4 markers on the bike that accurately locate the bike plane in each frame of the capture. It was designed for precision in both static and free-motion trainers and it provides a robust calculation of the bike plane regardless of its movement. It can be found on the 3DMA packages after v. 2019.0 as the Bike fitting (Full-body + bike) protocol.

This protocol was used to collect the ground-truth data for the comparisons, since the underlying purpose of this study was to find out if the bike plane position and orientation could be estimated in alternative ways after removing the bike and floor markers and still ensure robust output metrics.

C. Bike Fitting (Full-body)

This markerset uses 20 markers on the body in the same configuration as the previous models without extra markers on the floor or the bike. It can be found on the 3DMA packages after v. 2019.0 as the Bike fitting (Full-body) protocol.

The estimation of the bike plane relies on two key aspects or conditions. First, the wrists are assumed to be stable (they are arguably the only tracked landmarks that remain static regarding the bike throughout the capture) and symmetrically placed on the handlebar; the midpoint between wrists has been monitored and reveals a lateral shift of up to 8 mm and a anterior-posterior shift of up to 3 mm for 90% of the data of a sample trial (Fig. 4). An asymmetrical placement of the wrists or the movement of one or both arms, could cause an offset in the midpoint that will alter the resulting data.

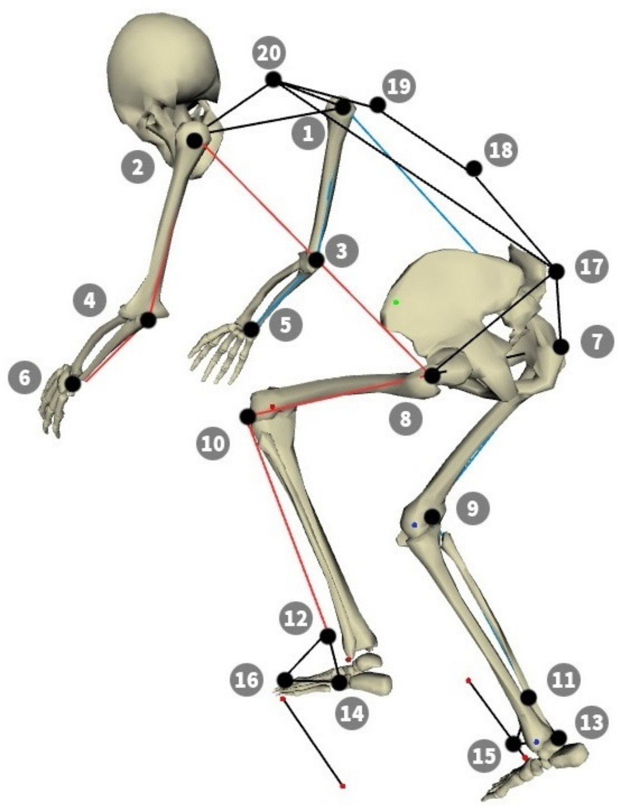

Fig. 2. Body markerset used for the captures. 20 markers in the following positions: Right/left shoulders, right/left elbows, right/left wrists, right/left great trochanters, right/left femoral epicondyles, right/left lateral malleoli, right/left side of the foot, right/left side of the 5th metatarsal, sacrum, L1 vertebrae, T7 vertebrae and C7 vertebrae.

Fig. 3. Bike markersets used for the captures. In blue: floor markers. In green: simplified bike markers. In red: complete bike markers.

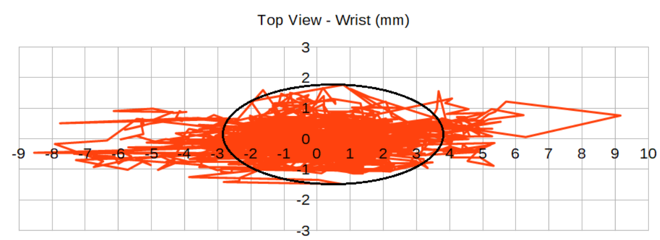

Fig. 4. Superior view of the wrists midpoint in orange, a circle containing 90% of the data shows the range of motion of the midpoint.

Second, both pedal axle markers, besides being the most stable points on the foot due to their short relative distance to shoe cleats, describe trajectories which, although potentially not identical because of the different adjustment of the cleat and foot motion, exhibit a midpoint that is located on the bike plane; this midpoint has been observed to shift up to 8 mm sideways and up to 6 mm vertically for 90% of the data of a sample trial (Fig. 5).

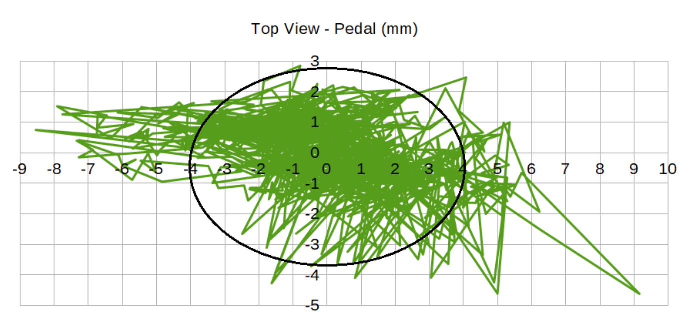

Fig. 5. Superior view of the pedals midpoint in green, a circle containing 90% of the data shows the range of motion of the midpoint.

A segment connecting the wrists midpoint and the pedal axles midpoint will always be contained on the bike plane, and the projection of this segment onto the calibrated floor will result in a vector that follows closely the bike position and orientation. The observed lateral shift in both midpoints has little repercussion on the vector direction and therefore on posterior parameter calculations, since the midpoints shift laterally predominantly in the same direction. A general view of the trajectories of both midpoints in relation to the actual movement of the pedal markers is shown on Figure 6.

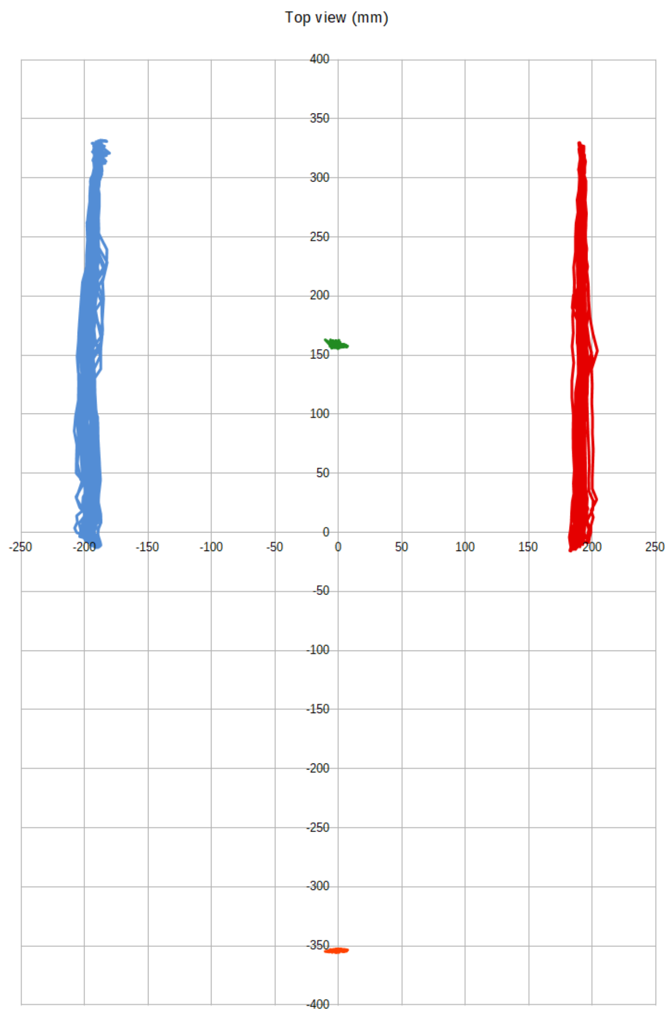

Fig. 6. Superior view of the points used for the estimation of the bike plane. The midpoint of the wrists in orange, the midpoint of the pedals in green, and for scale, the right and left pedal marker traces (in blue and red, respectively).

III. Overview of Body Kinematics and Their Sensitivity to Bike Motion

All biomechanical parameters are calculated in the same way across the three different protocols, but a distinction needs to be made between metrics that are affected by the bike positioning in space and metrics that are independent from it.

Some parameters do not require the use of the bike as a reference plane for their calculation, this means that when the reference frame is modified as it is between the three protocols, these parameters remain unchanged (Table II).

TABLE II
Variables unaffected by the bike plane

Group	Variables
Direct angle measurement or using absolute references such as the calibrated floor	Joint flexions Height differences Segment tilts Absolute distances
Anthropometric measurements	Femoral & tibial lengths Arm & forearm lengths Back dimensions

Some other parameters, however, do require the use of a reference plane, either the bike plane or a plane related to it such as the lateral plane (Table III).

TABLE III
Variables affected by the bike plane

Group	Variables
Angles projected on the sagittal plane. That is, on the bike plane and therefore directly affected by its definition.	Foot & pelvis rotation Crank angles Arm angle vs. sagittal plane Hip setback
Lateral distances from body landmark to the bike plane. Indirectly affected by the definition of the bike plane since the lateral axis is determined as orthogonal to the bike plane.	Knee lateral oscillations Shoulder lateral oscillations
Relative distances between body landmarks. Indirectly affected by the definition of the bike plane since the lateral axis is determined as orthogonal to the bike plane.	Trochanter-ankle lat. oscillation Knee-foot lat. oscillation Trochanter-knee lat. oscillation Hip vertical oscillation Trochanter-foot lat. oscillation Pelvic vertical oscillation Hip-wrist horizontal & vertical dist. Wrist-shoulder/elbow lat. oscillations
Fore Aft distances. Affected by the projection of anatomical points onto the bike plane.	Shoulder fore-aft movement Pelvis fore-aft movement KOPS

IV. Comparison Scenarios

After selecting the variables that had to be verified for possible error (Table III), a series of comparisons were performed in order to quantify the error introduced to the Bike Fitting (Full-body + floor) protocol (from now on referred to as Floor Markers protocol) and Bike Fitting (Full-body) protocol (from now on referred to as Body Markers protocol) when comparing them to the direct tracking of the bike using the Bike Fitting (Full-body + bike) protocol (from now on referred to as Bike Markers protocol).

The tests were performed and recorded with all the markers in place, and then manually labeled using the 3DMA software to differentiate them into each of the individual protocols, this way it was ensured that the source data was exactly the same for each comparison.

A. Bike Fitting (Full-body + floor) vs. (Full-body + bike) in the free-motion trainer

The first comparison that was conducted was between the results obtained using the Bike Markers protocol (as a gold standard) and the equivalent information provided by the Floor Markers protocol.

The purpose of this test was to gauge the magnitude of error that could be produced by using the Floor Markers protocol with a free-motion trainer instead of a static one, which is the one it was designed for.

One of the expected results was that the absolute lateral oscillations (calculated for the knees only) would be the variables with the most error, since the bike is not settled on the static reference axis throughout almost the entirety of the capture.

As for the rest of the variables that are calculated by plane projections, the error was expected to be less notorious but still somewhat present, considering that the free-motion trainer allows the bike to slightly tilt away from the static axis between 3 to 5 degrees with every direction change.

B. Bike Fitting (Full-body) vs. (Full-body + bike) in the free-motion trainer

The gold standard was also compared to the results obtained while avoiding the use of any bike or floor markers (Body Markers protocol). The calculation of a bike plane using the cyclist markers allows for slightly more error than actually tracking the position of the bike itself, but the tests were performed in order to measure this difference and evaluate if it was equally or less significant than the one between the Floor Markers protocol and the gold standard, specifically for its use in a free-motion trainer.

The expected results were an improvement on the calculation of absolute lateral oscillations and slight changes in the projected distances and angles but not enough to be significant for the worse.

C. Bike Fitting (Full-body + floor) vs. (Full-body + bike) in the static trainer

The previous comparisons were repeated using a static trainer. In the case of the Floor Markers protocol, the expected results were low error, since the protocol was designed for a static trainer and the bike was carefully aligned with the floor markers in all the captures.

The main purpose of this comparison was to understand the baseline error present in the recording of a static bike with static floor markers and compare it to the error that would appear when those floor markers were removed.

D. Bike Fitting (Full-body) vs. (Full-body + bike) in the static trainer

The last comparison was between the gold standard and the Body Markers protocol while on a static trainer. In this scenario, the Body Markers protocol was expected to calculate the position and orientation of a static bike almost as accurately as the Floor Markers protocol does.

Naturally, because the floor markers were removed, some additional error was expected. However, the main goal of the creation of the Body Markers protocol was to simplify the cyclist setup with minimal repercussion on the data.

V. Results & Discussion

The resulting data for the free-motion trainer and the static trainer was analyzed independently since the captures were performed separately, with different subjects and different cadences. The resulting findings are explained as follows.

A. Free-motion trainer experiments

To simplify the analysis of the data, the resulting errors from the comparisons were split in 3 categories: **Rotations** (measured in degrees and containing all the variables listed in Table III that were defined as rotations), **relative distances** (measured in millimeters and containing all the variables listed in Table III that were defined as distances between body landmarks projected to a plane) and **absolute distances** (measured in millimeters and containing all the variables listed in Table III that were defined as distances between a body landmark and the reference system).

1) Rotations: Upon revising the resulting error from comparing both Floor Markers and Body Markers protocols with the gold standard, the error registered was comparable between the two and remained under 2° for the captures collected on the free-motion trainer as shown in Figure 7.

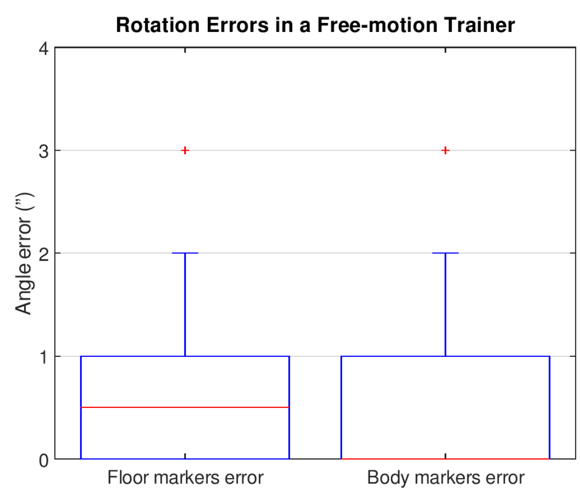

Fig. 7. Boxplot of the resulting differences between the Gold Standard and the Floor Markers (left) and Body Markers (right) protocols for rotation variables in a free-motion trainer.

The data on Figure 7 shows that the Body Markers protocol can estimate the bike orientation as well as the Floor Markers protocol in a free-motion trainer, and even though both present some error compared to the Bike Markers protocol, it is not a significant one.

2) Relative Distances: In the case of relative distances in the free-motion trainer, the movement of the bike during a trial introduces error when the method for bike tracking is not direct. This happens because the bike strays from the predefined bike plane (set by the floor markers) or because the bike estimation is not exactly oriented as the real bike is in every frame (in the Body Markers protocol).

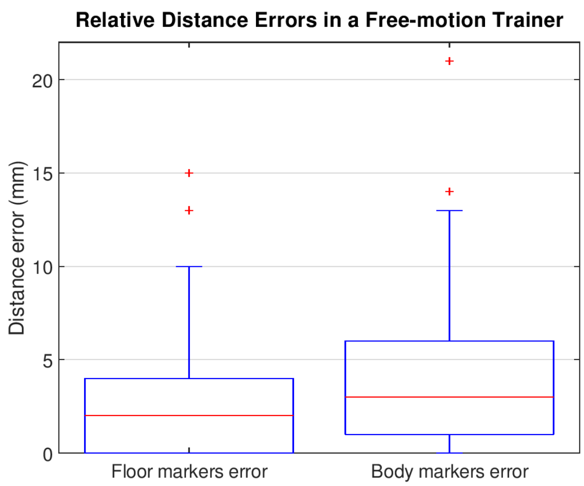

Fig. 8. Boxplot of the resulting differences between the Gold Standard and the Floor Markers (left) and Body Markers (right) protocols for relative distance variables in a free-motion trainer.

As shown in Figure 8, removing the floor markers accounts for 3mm of the final error of the Body Markers protocol, suggesting that what remains is caused by the difference between the movement of the bike throughout the capture and the movement of the estimated bike in both scenarios. It is important to clarify that 75% of these measurements were under 4mm for the Floor Markers protocol and under 6mm for the Body Markers protocol.

3) Absolute Distances: Since the Floor Markers protocol was not originally designed to be used with a free-motion trainer, the results obtained from this comparison reflected the issues that were corrected by the introduction of both the Bike Markers and Body Markers protocols.

As it is shown in Figure 9, the Floor Markers protocol is unable to obtain accurate measurements of absolute distances because it uses a fixed axis to estimate a moving bike. The Body Markers protocol, however slightly off by up to 5mm, manages to follow the position of the bike well enough to outperform the Floor Markers protocol if used on free-motion trainers.

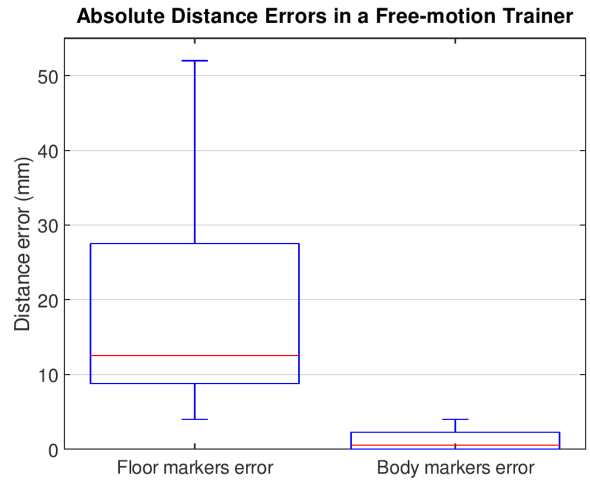

Fig. 9. Boxplot of the resulting differences between the Gold Standard and the Floor Markers (left) and Body Markers (right) protocols for absolute distance variables in a free-motion trainer.

B. Static trainer experiments

The data from the static trainer tests was separated in the same categories as the free-motion trainer data. The results are presented in the following graphs.

1) Rotations: Similar to how they were observed to behave in the free-motion trainer, the rotation variables errors remained mostly under 2° and with comparable distributions for both Floor Markers and Body Markers protocols, as shown in Figure 10.

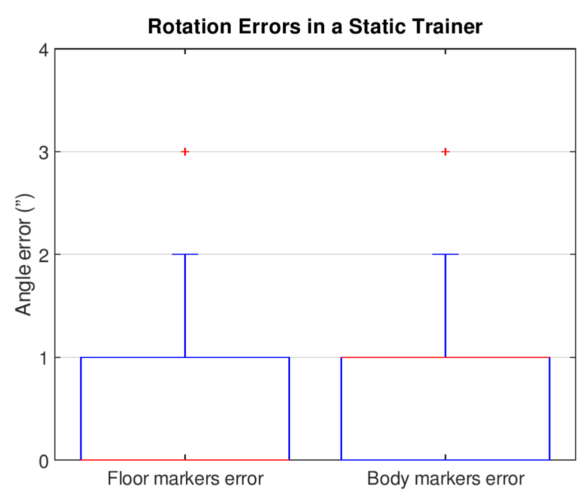

Fig. 10. Boxplot of the resulting differences between the Gold Standard and the Floor Markers (left) and Body Markers (right) protocols for rotation variables in a static trainer.

2) Relative Distances: In the case of relative distance errors, the Floor Markers protocol outperformed the Body Markers one possibly due to the influence of the slightly asymmetrical positioning of the wrists and feet on the bike plane calculations.

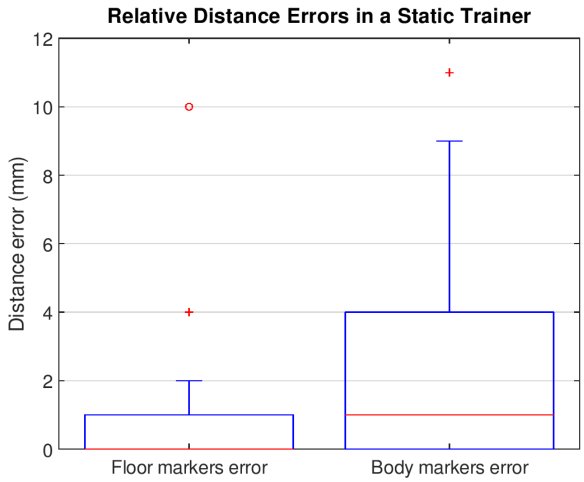

Fig. 11. Boxplot of the resulting differences between the Gold Standard and the Floor Markers (left) and Body Markers (right) protocols for relative distance variables in a static trainer.

The difference between the two (as shown in Figure 11) for 75% of the data was up to 4mm, and both protocols performed better with a static trainer than they did with the free-motion one, which suggests that the bike motion range has an effect on the resulting data.

3) Absolute Distances: Finally, the expected error difference for the protocols was not expected to be as high for the static trainer test as it was for the free-motion trainer ones, because the bike itself was not moving throughout the capture and neither was the reference frame. Both protocols resulted in comparable errors when compared to the gold standard (the Body Markers protocol also comparable to the same test performed on the free-motion trainer). The results are shown in Figure 12.

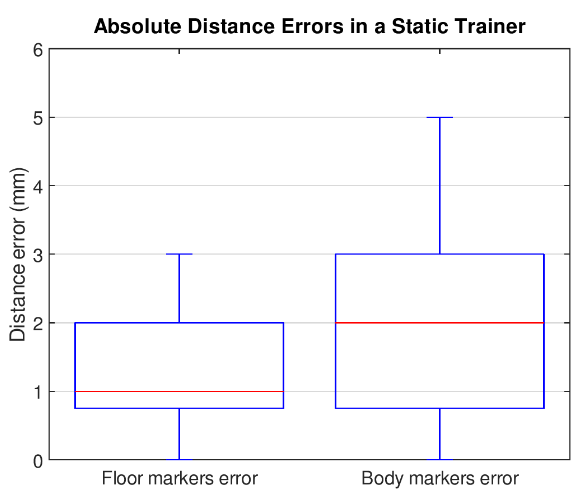

Fig. 12. Boxplot of the resulting differences between the Gold Standard and the Floor Markers (left) and Body Markers (right) protocols for absolute distance variables in a static trainer.

VI. Conclusions

Rotations of all protocols are comparable to each other (under 2°) for both types of trainers.

Relative distances are better measured by both indirect tracking protocols when using a static trainer but the difference is from 4 to 8 mm.

Absolute distances are not meant to be measured by the floor markers protocol when using a free-motion trainer: both the body markers and the bike markers protocols are useful alternatives when using a free-motion trainer. For simplicity go with body markers and for precision go for bike markers.

Absolute distances are measured accurately by all three protocols in a static trainer. The body markers protocol being the most likely to introduce error due to asymmetries in the posture of the cyclist but still only reaching a maximum of 5mm of error throughout the performed tests.

VII. Future Work

Perform a comprehensive study to compare all three protocols using captures from the same group of subjects, at controlled speeds and in the same location in order to eliminate all possible bias in the comparison of the protocols.