# Evaluation of 3D printed stabilizer for the Biodex: Effects on torque reliability and rate of force development

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*Abstract*—**Reliable ankle torque measurements are important in rehabilitation, where strength assessments are used to evaluate recovery and guide treatment. Isokinetic dynamometers, such as the Biodex system, are commonly used to provide controlled measurements of joint torque. However, these measurements rely on the ankle being held in a stable and reproducible position. Mechanical play in the ankle-attachment plate may therefore cause the angle of the ankle joint to deviate during testing, potentially contributing to measurement variability.**

**This project investigated whether a custom 3D printed stabilizer for the Biodex ankle-attachment plate could improve mechanical stability and measurement reliability during isometric tests of ankle plantarflexion and dorsiflexion. The project was performed at MoRe Lab, Biomedical Centre, Lund University. Five healthy participants completed test-retest measurements with and without the stabilizer. Peak torque and average peak torque were analyzed using intraclass correlation coefficients (ICC) and coefficient of variation of the typical error (CVTE). A separate dataset was also collected to compare the ankle angle recorded by the Biodex system with the actual ankle angle estimated from video analysis. The same dataset was used to analyze whether the stabilizer affected early and late rate of force development (RFD).**

**The results showed that the stabilizer reduced the discrepancy between the Biodex angle output and the ankle angle estimated from video analysis, although the reduction was small, approximately half a degree for peak angular difference. Test-retest reliability for peak torque and average peak torque was good to excellent in all conditions, but the stabilizer did not consistently improve ICC or CVTE. In contrast, RFD was significantly higher with the stabilizer during plantarflexion, but not during dorsiflexion.**

## I. Introduction

Ankle strength is essential during activities such as walking, running, and jumping. Two fundamental movements of the ankle are plantarflexion and dorsiflexion. As illustrated in Figure 1, dorsiflexion is movement of the foot upwards towards the body, while plantarflexion is movement of the foot downwards away from the body [1]. The ability to generate force during these movements is important for both everyday mobility and athletic performance.

Within clinical and sports rehabilitation, assessment of ankle strength is used to compare function of the injured and uninjured limb, and support decisions regarding progression in rehabilitation. For athletes, the function of the ankle is not only related to maximal strength, but also to the ability to produce force rapidly during tasks such as acceleration, jumping and changes of direction. Therefore, measurements that capture both maximal strength capacity and rapid force production provide valuable information when evaluating recovery and determining if an athlete is ready to return to their sport [2]. However, for such measurements to be useful, they must be reliable and reproducible across repeated tests.

Inlämnat den 6 juni 2026
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Svensk titel: Utvärdering av en 3D printad stabilisator för Biodex: påverkan på tillförlitligheten av vridmomentsmätningar och kraftutvecklingshastighet


Figure 1. Illustration of dorsiflexion and plantarflexion. Image used from [1].

Previous test-retest reliability studies have evaluated the reliability of isokinetic dynamometers, which are considered the gold standard when measuring torque for the ankle joint during plantarflexion and dorsiflexion. Reported reliability varies depending on the testing protocol and the specific joint movement being assessed, but it generally ranges from moderate to excellent [3] [4]. However, these validation studies typically rely on standard testing configurations and do not explicitly evaluate how mechanical stability of the ankle-attachment plate itself influences measurement consistency. Investigating whether improved stabilization affects the reliability of torque measurements and rate of force development (RFD) may therefore provide valuable methodological insight for both research and clinical applications.

### A. The Biodex system

Isokinetic dynamometers are widely used in both research and clinical settings to assess ankle strength, and the Biodex system is one example of such a device. During flexion-extension ankle testing, the participant's foot is secured to an ankle-attachment plate, and the system records torque while the participant performs either plantarflexion or dorsiflexion. These movements can be assessed under different testing conditions, such as isometric and isokinetic. In an isometric test, the joint is held at a fixed position while the participant produces force. This type of test is used to assess maximal torque production at a specific joint angle [3]. In an isokinetic test, the dynamometer moves through a predefined range of motion at a constant angular velocity while the participant produces force throughout the movement [5]. Although both testing conditions can provide valuable information, this project focuses on isometric measurements at a neutral ankle position (90°).

Biodex output from the ankle test included a torque-time curve, from which several outcome variables can be extracted. Peak torque represents the highest torque value reached during a contraction and is commonly used as a measure of maximal strength. Average peak torque can be calculated across repeated trials to reduce the influence of variability from a single trial. Additionally, the early part of the torque curve can be used to calculate the rate of force development (RFD), which describes how rapidly force is produced after onset of contraction. For this project, early RFD is defined from onset to 100 ms, while late RFD is 100 to 200 ms [6]. These time intervals are used to assess both the initial and later phases of rapid force production.

Although peak torque provides information about maximal force capacity, it does not describe how rapidly force can be produced. This distinction is relevant in rehabilitation since an injured limb may recover maximal torque while still showing impaired RFD, thus, showing strength is not the only descriptor that should be used when evaluating participants' return to activity [2].

Previous test-retest studies with the Biodex have reported good reliability, with results varying depending on protocol, joint position, and movement direction. Santy et al. reported excellent reliability for isometric plantarflexor peak torque at neutral ankle position, and good reliability when the ankle was tested in a more plantarflexed position, suggesting that joint angle influences measurement reproducibility [3]. Jenner et al. examined lower limb strength in female athletes and found that ankle plantarflexion generally showed moderate to good reliability, whereas dorsiflexion showed poor to moderate reliability [4]. On the other hand, Simpson et al. showed that peak torque had excellent test-retest reliability during isometric ankle dorsiflexion [7].

### *B. Measurement reliability and the importance of joint position*

A fundamental assumption when performing ankle torque measurements with an isokinetic dynamometer is that the ankle joint is positioned at a well-defined and reproducible angle. In practice, the foot is secured to an ankle-attachment plate and the device is set to a predefined joint position. However, due to individual anatomical differences and limitations in the mechanical setup, the actual ankle angle may deviate from the angle indicated by the device.

This is important as torque is influenced by joint angle through changes in muscle length and the moment arm of the muscle, thereby altering the plantarflexion moment produced around the ankle joint [8]. Even small deviations in joint position may therefore affect the measured torque and contribute to measurement variability.

### *C. Mechanical instability of the ankle-attachment plate*

During isometric ankle testing, the Biodex ankle-attachment plate is expected to maintain the foot in a fixed position while the participant applies force. However, the ankle-attachment plate used in this project showed approximately 3° of mechanical play. In addition to this local instability, further deviation of the angle can occur when higher forces are applied, as the arm for the ankle-attachment plate and the Biodex stand itself flexes under load. As a result, the actual ankle angle may deviate from the intended neutral position during testing.

This introduces additional measurement variability in peak torque. RFD may also be affected, as it is calculated from the early phase of the torque-time curve and is sensitive to disturbances in the measurement setup. Consequently, evaluating whether improved stabilization of the ankle-attachment plate reduces variability in peak torque and improves RFD measurement accuracy is important for assessing the setup's reliability and accuracy.

### *D. Aim of the project and hypothesis*

This project aims to evaluate whether a custom 3D printed stabilizer for the Biodex ankle-attachment plate improves mechanical stability and measurement reliability during isometric ankle torque testing at neutral ankle position (90°). Three analyses were performed. First, a position analysis compared the ankle angle reported by the Biodex system with the ankle angle determined from video analysis using Kinovea. Second, test-retest reliability was assessed for peak torque and average peak torque during plantarflexion and dorsiflexion. Lastly, rate of force development (RFD) was analyzed to investigate whether the stabilizer influenced rapid force production during isometric ankle testing, with early RFD defined as onset to 100 ms and late RFD defined as 100 to 200 ms.

The hypothesis is that the stabilizer will reduce the angle deviation and measurement variability, leading to better agreement between the Biodex angle output and the externally measured ankle angle, as well as improved reliability of torque-based outcomes.

## II. Materials and Methods

### *A. Study design*

The measurements were performed at MoRe Lab, located at the Biomedical Centre (BMC) at Lund University. The project consisted of two sets of data, a test-retest reliability dataset and a RFD and position dataset.

The test-retest reliability dataset included five participants and was used to evaluate the test-retest reliability of isometric ankle plantarflexion and dorsiflexion torque measurements. During two different visits, measurements were performed both with and without a custom 3D printed stabilizer mounted to the Biodex ankle-attachment plate. This dataset was used for the analysis of peak torque and average peak torque.

The RFD and position dataset was collected due to a synchronization issue identified in the test-retest reliability dataset, which made the analog data inaccessible for the position and RFD analysis. The RFD and position dataset was used to analyze rate of force development (RFD) and for position comparison between the ankle angle from the Biodex and the camera via Kinovea.

### B. Participants

Five participants were recruited for the test-retest reliability analysis. All participants were healthy adults (4 males, 1 female) with no current lower limb injury that would affect their ability to perform maximal isometric ankle plantarflexion or dorsiflexion. Both legs were tested for each participant during both visits. Before testing, participants were informed about the experimental procedure and instructed to perform each contraction with maximal effort.

For the RFD and position analysis, two participants (1 male, 1 female) from the test-retest reliability dataset were tested again.

### C. Experimental setup and equipment

All measurements were performed using a Biodex Advantage BX System 4 dynamometer. The Biodex ankle-attachment plate was used to secure the participant's foot during isometric plantarflexion and dorsiflexion testing. During each trial, the Biodex provided analog output signals corresponding to torque, angular velocity and position.

Data was collected using Qualisys Track Manager (Qualisys 2025.2). The analog Biodex signals were transferred through a Noraxon Analog Input System (AIS) and recorded together with video footage from a Qualisys Miqus camera. A Qualisys sync unit, power injector R2, and power unit were used to synchronize, stream and power the recording setup. Data collection was initiated using a trigger pulse, ensuring that the Biodex signals and video recording were synchronized at the start of each trial.

The complete hardware setup is illustrated in Figure 2. This setup allowed the mechanical behavior of the ankle-attachment plate to be recorded simultaneously with the Biodex output signals, enabling later comparison between position data reported by the Biodex and ankle angle determined from the video footage.

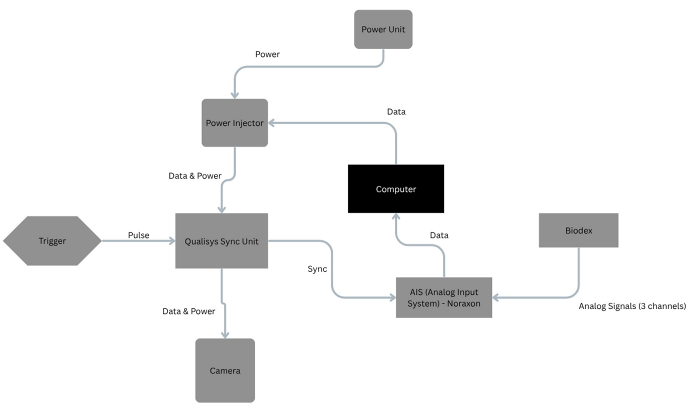


Figure 2. A schematic overview of the hardware setup.

### D. Stabilizer design and test conditions

A custom 3D printed stabilizer was developed to reduce mechanical play in the Biodex ankle-attachment plate. The stabilizer was designed as an insert that could be mounted directly to the ankle-attachment plate without changing the standard Biodex testing setup (Figure 3).

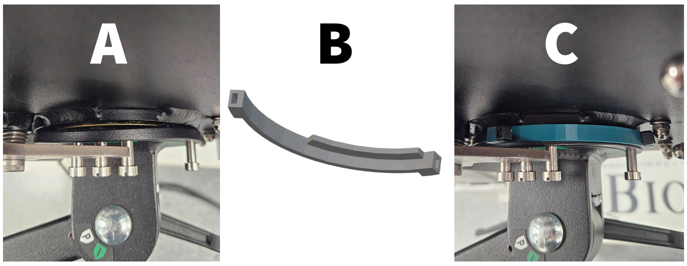


Figure 3. The stabilizer and its placement in the Biodex ankle-attachment setup. (A) Ankle-attachment plate without the stabilizer. (B) CAD model of stabilizer. (C) Stabilizer mounted to the ankle-attachment plate.

Two conditions were tested: with stabilizer and without stabilizer. In the stabilizer condition, the insert was mounted before testing, whereas in the non-stabilizer condition the ankle attachment was used in its standard configuration. The same isometric plantarflexion and dorsiflexion protocol was performed under both conditions.

### E. Testing protocol

Participants were seated in the Biodex chair with the tested foot secured to the ankle-attachment plate. For the tested leg, the knee was flexed approximately 65-70° to position the tibia as close to parallel with the ground as possible, while maintaining a comfortable position. The lateral malleolus was aligned with the dynamometer's axis of rotation. The thigh support pad was positioned to minimize force contribution from other muscles in the leg, ensuring that the test primarily assessed ankle plantarflexion and dorsiflexion torque (Figure 4).

Figure 4. Setup of participant in chair.

Each participant completed isometric plantarflexion and dorsiflexion trials for both legs under two testing conditions: with and without the stabilizer. For each condition, one leg was tested first, followed by the other. Participants were instructed to push with maximal effort during each trial. A short familiarization period was performed before the recorded trials to ensure that participants understood the task.

*1) Test-retest reliability dataset:* Each participant performed three repetitions of plantarflexion and dorsiflexion on each leg for both stabilizer conditions. The order of the starting leg and the order of the stabilizer condition were randomized for each participant. The same testing procedure was repeated during a second visit, separated by at least seven days.

*2) RFD and position dataset:* Each participants performed five repetitions of plantarflexion and dorsiflexion for each leg and stabilizer condition during both visits. Reflective markers were placed on the lateral malleolus and near the femoral condyle to later be used for ankle angle analysis in Kinovea.

To reduce the influence of potential order effects (e.g. fatigue, learning, or neuromuscular priming), the order of the stabilizer condition was reversed between visits. If a participant started with the stabilizer condition during the first visit, the same participant started without the stabilizer during the second visit, and vice versa.

### *F. Ankle position analysis*

The video data was analyzed in Kinovea to estimate the ankle angle during each trial. The angle determined from the video footage was compared with the position output from the Biodex to evaluate the discrepancy between the two measurements.

For each trial, the discrepancy was summarized using three measures: mean absolute difference, peak absolute difference, and standard deviation of the difference. These outcomes were used to assess whether the stabilizer reduced the discrepancy between the Biodex angle output and the externally measured ankle angle.

### *G. Signal processing and outcome measures*

Peak torque and average peak torque were obtained directly from the Biodex reports saved after each condition. Peak torque was defined as the highest torque value recorded from three trials, while average peak torque represented the average of the peak torque values across the three trials, within the same testing condition.

For the RFD and position dataset, data from the Biodex analog channels were collected as raw voltage signals and processed in MatLab (R2024a). This data was used for the calculations of early RFD, late RFD and for analysis of the ankle position from the Biodex system.

### *H. Statistical analysis*

*1) Test-retest reliability analysis:* Test-retest reliability was assessed for peak torque and average peak torque using intraclass correlation coefficients (ICC) and coefficient of variation of the typical error (CVTE). Analyses were performed separately for each stabilizer condition, movement direction, and leg. This resulted in separate reliability analyses for plantarflexion and dorsiflexion, right and left leg, with and without the stabilizer [5].

ICC was calculated using a two-way mixed-effects model with absolute agreement and single measures. A 95% confidence interval was reported for each ICC. Reliability values greater than 0.90 were interpreted as excellent, values between 0.75 and 0.90 as good, values between 0.50 and 0.75 as moderate, and values below 0.50 as poor [5]. Statistical analysis was conducted using IBM SPSS Statistics.

*2) RFD analysis:* RFD was analyzed using a linear mixed-effects model because several repeated contractions were collected from the same participants, thus, the observations could not be treated as fully independent [9]. Stabilizer condition, RFD phase, movement direction, and their interaction were included as fixed effects. Visit and side were also included as fixed effects, while Participant was included as a random effect. Estimated marginal means were used to compare RFD with and without the stabilizer for early and late RFD during plantarflexion and dorsiflexion. The condition-by-phase interaction was used to evaluate whether the stabilizer affected early and late RFD differently. Statistical analysis was conducted using IBM SPSS Statistics.

*3) Position analysis: Biodex vs. video analysis:* The position analysis was performed using the RFD and position dataset. The ankle angle reported by the Biodex was compared with the ankle angle determined from video analysis using Kinovea. For each trial, mean absolute difference, peak absolute difference, and standard deviation of the difference were calculated.

## III. Results

### *A. Position analysis: Biodex vs. video analysis*

The stabilizer condition showed lower discrepancies between the Biodex angle output and the externally measured ankle angle compared with the non-stabilizer condition (Table I). Mean absolute difference decreased from 4.68° to 4.38°, peak absolute difference decreased from 7.51° to 6.99°, and the standard deviation of the difference decreased from 2.71° to 2.53°. Overall, the reductions were less than 1° for all three measures, corresponding to relative reductions of approximately 6.5-6.9%.

Table I
Overall position analysis in degrees: with and without stabilizer. Values are reported in degrees.

| Measure | W/ stab. | W/o stab. | Diff. | Rel. red. (%) |
|---|---|---|---|---|
| MeanAbsoluteDiff | 4.38 | 4.68 | 0.30 | 6.50 |
| PeakAbsoluteDiff | 6.99 | 7.51 | 0.52 | 6.90 |
| StdDiff | 2.53 | 2.71 | 0.18 | 6.60 |

w/ = with, w/o = without, stab. = stabilizer, Diff. = difference, Rel. red. = relative reduction.

When plantarflexion and dorsiflexion were analyzed separately, the stabilizer condition showed lower discrepancies for both movements (Table II). For plantarflexion, the mean absolute difference decreased from 3.92° to 3.51°, corresponding to a relative reduction of 10.5%. For dorsiflexion, the mean absolute difference decreased from 5.46° to 5.24°, corresponding to a relative reduction of 4.0%. Peak absolute difference and standard deviation of the difference were also lower with the stabilizer in both movement directions.

Table II
POSITION ANALYSIS BY MOVEMENT DIRECTION. VALUES ARE REPORTED IN DEGREES.

| Movement | Measure | W/ stab. | W/o stab. | Diff. | Rel. red. (%) |
|---|---|---|---|---|---|
| PF | MeanAbsoluteDiff | 3.51 | 3.92 | 0.41 | 10.50 |
| PF | PeakAbsoluteDiff | 6.64 | 7.15 | 0.52 | 7.20 |
| PF | StdDiff | 3.08 | 3.26 | 0.18 | 5.50 |
| DF | MeanAbsoluteDiff | 5.24 | 5.46 | 0.22 | 4.00 |
| DF | PeakAbsoluteDiff | 7.35 | 7.88 | 0.53 | 6.80 |
| DF | StdDiff | 1.99 | 2.15 | 0.16 | 7.60 |

PF = plantarflexion, DF = dorsiflexion. w/ = with, w/o = without, stab. = stabilizer, Diff. = difference, Rel. red. = relative reduction.

When analyzed separately for each participant, the reduction in discrepancy between the Biodex angle output and the externally measured ankle angle differed between the two participants (Table III). For Participant 1, the mean absolute difference decreased from 3.17° without the stabilizer to 2.53° with the stabilizer, corresponding to a relative reduction of 20.1%. For Participant 2, the corresponding reduction was considerably smaller, with the mean absolute difference decreasing from 6.23° to 6.22°, corresponding to a relative reduction of merely 0.2%.

Table III
POSITION ANALYSIS BY PARTICIPANT. VALUES ARE REPORTED IN DEGREES.

| P | Measure | W/ stab. | W/o stab. | Diff. | Rel. red. (%) |
|---|---|---|---|---|---|
| 1 | MeanAbsoluteDiff | 2.53 | 3.17 | 0.64 | 20.10 |
| 1 | PeakAbsoluteDiff | 5.04 | 5.69 | 0.66 | 11.50 |
| 1 | StdDiff | 2.39 | 2.48 | 0.09 | 3.70 |
| 2 | MeanAbsoluteDiff | 6.22 | 6.23 | 0.01 | 0.20 |
| 2 | PeakAbsoluteDiff | 8.95 | 9.38 | 0.43 | 4.60 |
| 2 | StdDiff | 2.68 | 2.95 | 0.27 | 9.20 |

P = Participant, w/ = with, w/o = without, stab. = stabilizer, Diff. = difference, Rel. red. = relative reduction.

### B. Test-retest reliability

The stabilizer condition did not consistently improve test-retest reliability across all outcomes. Some comparisons showed lower CVTE with the stabilizer than without, particularly plantarflexion and dorsiflexion for the right leg, whereas other comparisons showed equal or better reliability without the stabilizer. Overall, both conditions demonstrated generally good to excellent ICC values, but the wide confidence intervals indicate uncertainty due to the small sample size (Table IV, V).

Table IV
TEST-RETEST RELIABILITY FOR PEAK TORQUE.

| Case | Movement | Side | ICC | 95% CI | p-value | CVTE (%) | Interp. |
|---|---|---|---|---|---|---|---|
| W/ stab. | PF | Right | 0.80 | -0.07–0.98 | 0.006 | 7.92 | Good |
| W/ stab. | PF | Left | 0.85 | 0.25–0.98 | 0.013 | 11.60 | Good |
| W/ stab. | DF | Right | 0.94 | 0.56–0.99 | 0.004 | 4.88 | Excellent |
| W/ stab. | DF | Left | 0.95 | 0.67–0.99 | 0.002 | 3.54 | Excellent |
| W/o stab. | PF | Right | 0.80 | 0.06–0.98 | 0.013 | 11.03 | Good |
| W/o stab. | PF | Left | 0.94 | 0.61–0.99 | 0.003 | 7.42 | Excellent |
| W/o stab. | DF | Right | 0.80 | -0.16–0.98 | 0.040 | 8.16 | Good |
| W/o stab. | DF | Left | 0.87 | 0.17–0.99 | 0.017 | 7.55 | Good |

PF = plantarflexion, DF = dorsiflexion. w/ = with, w/o = without, stab. = stabilizer, ICC = intraclass correlation coefficient, CI = confidence interval, CVTE = coefficient of variation of the typical error, Interp. = interpretation.

Table V
TEST-RETEST RELIABILITY FOR AVERAGE PEAK TORQUE.

| Case | Movement | Side | ICC | 95% CI | p-value | CVTE (%) | Interp. |
|---|---|---|---|---|---|---|---|
| W/ stab. | PF | Right | 0.76 | -0.09–0.97 | 0.009 | 9.16 | Good |
| W/ stab. | PF | Left | 0.85 | 0.26–0.98 | 0.013 | 11.44 | Good |
| W/ stab. | DF | Right | 0.94 | 0.59–0.99 | 0.003 | 4.65 | Excellent |
| W/ stab. | DF | Left | 0.94 | 0.55–0.99 | 0.001 | 3.25 | Excellent |
| W/o stab. | PF | Right | 0.77 | 0.02–0.97 | 0.021 | 12.77 | Good |
| W/o stab. | PF | Left | 0.95 | 0.68–0.99 | 0.002 | 6.84 | Excellent |
| W/o stab. | DF | Right | 0.84 | 0.06–0.98 | 0.024 | 6.90 | Good |
| W/o stab. | DF | Left | 0.88 | 0.20–0.99 | 0.015 | 7.34 | Good |

PF = plantarflexion, DF = dorsiflexion. w/ = with, w/o = without, stab. = stabilizer, ICC = intraclass correlation coefficient, CI = confidence interval, CVTE = coefficient of variation of the typical error, Interp. = interpretation.

### C. RFD analysis

RFD results for each participant and visit are presented in Table VI. The table summarizes early and late RFD for plantarflexion and dorsiflexion under both stabilizer conditions. For plantarflexion, RFD values were generally higher with the stabilizer than without the stabilizer, particularly for Participant 1 across both visits and for Participant 2 during Visit 1. For dorsiflexion, the differences between stabilizer conditions were smaller and less consistent.

Table VI
RFD MEASUREMENTS, WITH AND WITHOUT STABILIZER.

| P | Visit | Movement | Early RFD W/ stab. ± SD | Early RFD W/o stab. ± SD | Late RFD W/ stab. ± SD | Late RFD W/o stab. ± SD |
|---|---|---|---|---|---|---|
| 1 | 1 | PF | 252.3 ± 36.2 | 226.4 ± 58.0 | 211.5 ± 50.9 | 186.0 ± 32.6 |
| 1 | 1 | DF | 97.9 ± 8.6 | 99.2 ± 13.6 | 73.6 ± 8.3 | 75.2 ± 5.3 |
| 1 | 2 | PF | 270.4 ± 48.7 | 218.6 ± 39.5 | 219.3 ± 30.3 | 179.3 ± 28.6 |
| 1 | 2 | DF | 96.1 ± 19.2 | 101.3 ± 6.6 | 75.6 ± 6.6 | 76.0 ± 6.9 |
| 2 | 1 | PF | 664.9 ± 108.0 | 554.9 ± 52.0 | 404.7 ± 63.9 | 286.0 ± 66.4 |
| 2 | 1 | DF | 235.0 ± 29.0 | 209.1 ± 25.4 | 121.4 ± 15.3 | 114.9 ± 21.8 |
| 2 | 2 | PF | 566.9 ± 58.2 | 559.0 ± 75.8 | 299.0 ± 75.8 | 330.5 ± 84.8 |
| 2 | 2 | DF | 212.5 ± 17.1 | 217.6 ± 10.2 | 121.0 ± 14.8 | 123.9 ± 8.7 |

P = Participant, PF = plantarflexion, DF = dorsiflexion. SD = Standard deviation, w/ = with, w/o = without, stab. = stabilizer, RFD = rate of force development.

The linear mixed-effects model showed a significant difference between stabilizer conditions during plantarflexion, with higher RFD values observed with the stabilizer for both early RFD ($p = 0.003$) and late RFD ($p = 0.019$). For dorsiflexion, no significant difference between stabilizer conditions was found for either early RFD ($p = 0.817$) or late RFD ($p = 0.977$). (Table VII).

Table VII
EFFECT OF THE STABILIZER ON EARLY AND LATE RFD.

| RFD phase | Movement | W/ stab. (N/s) | W/o stab. (N/s) | Diff. (N/s) | p-value |
|---|---|---|---|---|---|
| Early RFD | DF | 160.86 | 157.06 | 3.81 | 0.817 |
| Early RFD | PF | 438.62 | 389.75 | 48.87 | 0.003 |
| Late RFD | DF | 99.14 | 98.68 | 0.47 | 0.977 |
| Late RFD | PF | 283.62 | 245.43 | 38.19 | 0.019 |

PF = plantarflexion, DF = dorsiflexion. w/ = with, w/o = without, stab. = stabilizer, Diff. = difference, RFD = rate of force development.

The condition-by-phase interaction was not significant (p = 0.889), indicating that the effect of the stabilizer did not differ significantly between early and late RFD. The condition-by-phase-by-movement interaction was also not significant (p = 0.825), indicating that difference between early and late RFD response did not differ significantly between plantarflexion and dorsiflexion.

## IV. DISCUSSION

### A. Position analysis: Biodex vs. video analysis

The position analysis showed that the stabilizer reduced the discrepancy between the Biodex angle output and the ankle angle determined from video analysis. However, the magnitude of the reduction was unexpectedly small. For both plantarflexion and dorsiflexion, peak absolute difference was reduced by approximately half a degree, which is considerably less than the approximately 3° of mechanical play observed in the ankle-attachment plate. One possible explanation is that the mechanical play in the ankle-attachment plate was not the dominant source of angular deviation during a maximal isometric test. Although the stabilizer reduced local instability in the ankle-attachment plate, other parts of the setup, such as the attachment arm and the Biodex system itself will still flex under load.

At first glance, the movement-specific results (Table II) may suggest that the stabilizer had a larger effect during plantarflexion than dorsiflexion. This could be explained by the fact that plantarflexion allows greater force production than dorsiflexion, potentially creating larger mechanical loads on the ankle-attachment plate and therefore making stabilization more relevant. However, this explanation is not sufficient on its own. Although it isn't a peak torque measurement, RFD was captured simultaneously and when looking at the results (Table VI) it shows that Participant 2 produced higher force development than Participant 1, yet the analysis separated by participant showed a better improvement for Participant 1 (Table III). This suggests that force magnitude alone does not explain the stabilizer's effect. Other individual factors, such as foot size, shoe contact, foot placement on the plate, and where force is applied, may also have influenced how much the stabilizer reduced angular deviation.

Furthermore, the video analysis introduces additional uncertainty. The video based angle measurements depend on marker placement and manual tracking decisions done in Kinovea. Since the observed reductions were small, measurement error in the video analysis may have influenced the results. Therefore, while the position analysis suggests that the stabilizer had a measurable effect, the results should be interpreted with caution since only two participants were included in this part of the study.

### B. Test-retest reliability

The test-retest reliability results showed good to excellent reliability for both peak torque and average peak torque in all conditions. This is consistent with previous studies, which have reported acceptable to excellent reliability for isometric ankle torque measurements using Biodex systems. However, the stabilizer did not produce a consistent improvement in ICC or CVTE. Some outcomes improved with the stabilizer, particularly during dorsiflexion, while others were similar or better without it.

This could be explained by the position analysis, where the stabilizer reduced the angular deviation of the ankle, but the effect was small. The small improvement was therefore not significant enough to translate into a clear or consistent improvement in ICC or CVTE. The deviation in variability may instead be explained by participant positioning, familiarization, day-to-day variation, or flexing in the attachment arm and Biodex system under load. Furthermore, the wide confidence intervals for several ICC values indicate uncertainty in the reliability estimates, likely due to the small sample size of five participants. Therefore, the results should not be interpreted as representative of a larger population, and further testing with more participants is needed to determine whether the stabilizer meaningfully improves test-retest reliability.

### C. RFD analysis

The RFD analysis showed a significant effect of the stabilizer during plantarflexion, with higher values observed for both early and late RFD. No corresponding effect was found for dorsiflexion. Since RFD is calculated over short time intervals immediately after contraction onset, it will be more sensitive to mechanical disturbances at the beginning of the contraction. If the ankle-attachment plate moves as the participant starts pushing, part of the initial force will be absorbed by plate movement rather than being transferred directly to the Biodex. In contrast, a more stable plate would provide firmer resistance at contraction onset, which may result in a higher measured rate of force development.

One possible explanation is that the ankle-attachment plate was not equally unstable in both movement directions. When the foot was secured in neutral position, the weight of the foot and plate may have naturally shifted the attachment towards the dorsiflexion direction, leaving less available play during dorsiflexion. This could explain why the stabilizer had a clearer effect during plantarflexion, where mechanical play appeared to be greater, than during dorsiflexion. However, since the RFD analysis included only two participants, these findings should not be interpreted as representative of a larger population.

### D. Sustainability and ethics

The stabilizer was manufactured using 3D printing, allowing rapid prototyping of a customized component with limited material use. From a sustainability perspective, improving existing equipment rather than replacing the full system will contribute to a more resource efficient clinical and research practice.

From an ethical perspective, accurate and reliable measurements are important in rehabilitation. When strength measurements are used to evaluate recovery and guide treatment, avoidable measurement errors may lead to misleading conclusions about a patient's physical capacity. If this results in the patient returning to activity prematurely, it can increase the risk of reinjury and place additional strain on the healthcare system. Improving measurement reliability is therefore an ethical responsibility in clinical and research settings. More broadly, this relates to the idea that sustainable development includes improving health, function, and quality of life, particularly for individuals who depend on rehabilitation to regain physical function.

## V. Conclusion

The stabilizer reduced the ankle angle deviation, but the magnitude of the reduction was small. Test-retest reliability for peak torque and average peak torque was good to excellent across conditions, but the stabilizer did not produce a consistent improvement in ICC or CVTE. In contrast, the RFD analysis showed higher values with the stabilizer during plantarflexion, suggesting RFD is sensitive to short mechanical disturbances in the ankle-attachment plate. Overall, the hypothesis was only partially supported: the stabilizer produced measurable improvements for ankle position and RFD, but did not clearly improve torque measurement reliability under the tested conditions.

## VI. Acknowledgements

I would like to thank my supervisor Daniel Benoit for entrusting me with this project and for his guidance and support, especially during the early stages. I would also like to give a special thanks to Elese St Louis, who has been of great help throughout the entire project, particularly during the long days of data collection and by processing all the raw Biodex data into usable outcome measures. I am also grateful to Nicholas, Jens, Jesper, and Elese for participating in the measurements and contributing their time to the study.

This project was carried out by Filip Mårtensson, including the development and 3D printing of the stabilizer, planning and execution of the experimental protocol, data analysis, and writing of the report.

## Referenser

[1] Cionic, "A beginner's guide to plantarflexion and dorsiflexion," 2023. [Online]. Available: https://go.cionic.com/a-beginners-guide-to-plantarflexion-and-dorsiflexion.

[2] M. Buckthorpe and G. S. Roi, "The time has come to incorporate a greater focus on rate of force development training in the sports injury rehabilitation process," *Muscles Ligaments Tendons J.*, vol. 7, no. 3, pp. 435–441, 2018.

[3] F.-M. Santy, A. Pernoud, S. Barrué-Belou, F. Fourchet, H. Bothorel, and P. Samozino, "Reliability of isokinetic dynamometer for isometric assessment of ankle plantar flexor strength," *Phys. Ther. Sport*, vol. 71, pp. 36–42, 2025.

[4] B. Jenner, C. Nottle, J. L. Walters, S. W. Saunders, A. S. Leicht, and R. G. Crowther, "Reliability of lower limb strength assessment in female team sport athletes," *Phys. Ther. Sport*, vol. 68, pp. 71–79, 2024.

[5] J. Tuominen, M. Leppänen, H. Jarske, K. Pasanen, T. Vasankari, and J. Parkkari, "Test-retest reliability of isokinetic ankle, knee and hip strength in physically active adults using Biodex System 4 Pro," *Methods Protoc.*, vol. 6, no. 2, article 26, 2023.

[6] A. Saç, "Does the early and late rate of torque development, change in relation to the quadriceps angle?" *J. Educ. Train. Stud.*, vol. 7, no. 3S, 2019.

[7] D. Simpson, M. Ehrensberger, C. Nulty, J. Regan, P. Broderick, C. Blake, and K. Monaghan, "Peak torque, rate of torque development and average torque of isometric ankle and elbow contractions show excellent test-retest reliability," *Hong Kong Physiother. J.*, vol. 39, no. 1, pp. 67–76, 2018.

[8] D. Landin, M. Thompson, and M. Reid, "Knee and ankle joint angles influence the plantarflexion torque of the gastrocnemius," *J. Clin. Med. Res.*, vol. 7, no. 8, pp. 602–606, 2015.

[9] Z. Yu, M. Guindani, S. F. Grieco, L. Chen, T. C. Holmes, and X. Xu, "Beyond t test and ANOVA: applications of mixed-effects models for more rigorous statistical analysis in neuroscience research," *Neuron*, vol. 110, no. 1, pp. 21–35, 2022.