Determining friction forces with inertial measurement units from linear wheelchair rugby field data

by

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Preface

In front of you lies the master thesis focusing on the measurement of friction forces in wheelchair rugby. I worked on this thesis from February to September 2023 to fulfill the graduation requirements of the master 'Biomedical Engineering' at the TU Delft.

During process my graduation process, I gained several valuable experiences. Wheelchair rugby opened a new world to me. I learned how to work with inertial measurement units and expanded my knowledge of the software program Matlab. Working on the thesis reminded me repeatedly that accuracy is truly important, whether you are taking measurements, analyzing data or writing the report. Precision is not my strong suit, but I have fortunately been able to develop that over the past few months. To be honest, I have never really been enthusiastic about doing research, but through this project I have also seen positive parts. As it is valuable to have contact with athletes who may later benefit from the research you are working on. Besides, the feeling of happiness when you run a Matlab code without errors, is indescribable. I found graduation a tough but worthwhile process.

I could not have written this thesis without help. Therefore, I would like to express my thanks to my supervisor DirkJan first of all. He always helped me with my questions, and I appreciated his valuable insights. DirkJan encouraged me to think for myself and to keep my eyes on the goal. I also would like to thank my other supervisor, Marit. She was mainly involved during the start of my project and in the final stage. Marit kept me focused to be precise. She also helped me to keep the common thread in mind during the process. I would also like to thank Rienk for making me familiar with taking measurements during the Musholm cup in Denmark. Besides, he provided me with datasets and was always available for follow-up questions. Rienk also put me in touch with Melle and Daniel so I could run a pilot test on the Haagse Hogeschool. I appreciate all the help I received to perform my pilot test. Thank you Gerrieke, Laurene, Willemiek, Shevonne, Esther and Naine for participating. I would like to thank my fellow students Vera, Nathalie, Victor and Puck for all the feedback and ideas I received during our student meetings. A special thanks to Puck for your support during our study sessions at the library, I appreciate our discussions and your comments. I would like to thank Elisabeth, Yoni and Denise for proof-reading my thesis. I am also incredibly grateful for the mental support of my parents, roommates, friends, family and colleagues throughout the project.

I would like to end this preface with a Bible verse that reminds me Who gave me the strength and wisdom to complete this thesis:

> *"And whatever you do, whether in word or deed, do it all in the name of the Lord Jesus, giving thanks to God the Father through him."* - Colossians 3:17

I hope you enjoy reading my thesis,

Marije den Boer

Lopik, 26 September 2023

Abstract

Goal This study aimed to determine friction forces during linear deceleration periods in wheelchair rugby (WCR) field data with the use of Inertial Measurement Units (IMUs). Deceleration during a standardized coast-down was used as gold standard and compared to two other deceleration types. One was the non-standardized coast-down, a non-controlled linear deceleration in field data with little trunk movement. The other was sprint deceleration, referring to the decelerations during recovery phases in a sprint.

Method Nineteen elite WCR players performed a wheelchair mobility test on a rugby court. The test included a linear sprint and three coast-down tests. IMUs were placed on frame, wheel and trunk.

Standardized coast-down phases were selected by hand based on the wheelchair velocity signal. Non-standardized coast-down decelerations were selected automatically based on ranges in frame rotation, trunk movement, velocity, deceleration and duration. Sprint decelerations were selected automatically based on peaks in the wheelchair velocity signal.

Intraclass Correlation Coefficients (ICCs) were determined to assess the test-retest reliability of the standardized coast-down tests and to classify the agreement between the three deceleration types. Three Generalized Estimated Equations (GEEs) were performed for each deceleration type to study relations with velocity, frame rotation, trunk movement, mass and classification score.

Results The ICCs evaluating the quality of the standardized coast-down showed poor to excellent test-retest reliability. ICC = 0.507, 95% CI [0.180, 0.782] and ICC = 0.768, 95% CI [0.406, 0.968].

Standardized coast-down deceleration showed poor to moderate agreement with non-standardized coast-down deceleration (ICC = -0.280, 95% CI [-2.322, 0.507]) and with sprint deceleration (ICC = 0.166, 95% CI [-1.164, 0.679]).

The GEEs could not explain the deviations in deceleration values by the studied variables.

Conclusion The friction forces could not be reliably determined during linear decelerations, even for the standardized coast-down. The used methodology contains too many uncertainties for practical application and needs improvement.

Contents

List of abbreviations

CI	Confidence Interval
fs	Sample frequency
GEE	Generalized Estimated Equations
HP-player	High point player
IMU	Inertial Measurement Unit
ICC	Intraclass Correlation Coefficient
LP-player	Low point players
WCR	Wheelchair rugby
WCT	Wheelchair tennis
WMP	Wheelchair mobility performance

Introduction

In the 1970s, quadriplegic athletes in Canada searched for a sport that was accessible for athletes with impairments of both upper and lower limbs (1). The search led to the invention of wheelchair rugby (WCR). The sport continued to develop and since 2000, WCR is designated as an official Paralympic sport (2). Each WCR player in the team is classified according to the rules of the World Wheelchair Rugby (WWR) classification (1). The higher the classification score of the athlete, the more abled the athlete is. So called low-point (LP) players often play a more defensive role, while the high-point (HP) players play in the offense. It has been shown that LP players propel at lower velocities compared to HP players (3, 4). Defensive wheelchairs are also usually heavier and less agile compared to offensive wheelchairs which are used for fast accelerations and rotations. Hence, there are individual differences in wheelchair mobility performances (WMP) among WCR players. One of the factors limiting the WMP is the friction force of the wheelchair. Friction force is also related to the amount of power an athlete needs to propel the wheelchair (5). Power output is a measure of the amount of physical effort an athlete expends to move forward (6). For elite level WCR it is valuable to improve mobility performance and propel as efficiently as possible. Insights on individual friction forces during WCR match-setting can be used as a base for improving WMP by coaches and for the development of effective training methods. In addition, insights on friction forces can support choices in wheelchair features like alignment of the wheels and rear wheel camber to reduce the required power output.

For manual wheelchairs, resistive forces can be approached during an overground coast-down test based on deceleration measurements (7). Rietveld et al. (8) show that friction forces can be determined based on deceleration for standardized coast-down tests in wheelchair tennis (WCT), another wheelchair court sport. During a standardized coast-down, an athlete propels the wheelchair for a certain distance and then decelerates while sitting still with the hands placed on the lap.

In the study of Rietveld et al. (8), Inertial Measurement Units (IMUs) were used to determine deceleration during the standardized coast-down tests. IMUs are sensors that can measure linear acceleration, angular velocity and the orientation of the sensor based on an accelerometer, gyroscope and magnetometer. It is a relatively cheap and non-invasive way to map the acceleration, velocity and displacement of a wheelchair and/or an athlete in the field. For wheelchair court sports, IMUs can be used to measure wheelchair kinematics during matches (9).

In case of a standardized coast-down, propulsion force is absent and friction forces cause the wheelchair plus athlete to decelerate. Deceleration can thus be related to friction forces. A simplification of this relation according to Newtons' first law can be found in *Eq. (1).*

$$F_{friction} = m \cdot -a_x \qquad \textit{Eq. (1)}$$

$F_{friction}$ in this equation stands for the total friction force, m refers to the total mass of wheelchair plus athlete and $-\mathrm{a_x}$ is seen as the linear deceleration of the wheelchair. The total friction force of a wheelchair consists of the rolling resistance, air drag, internal friction forces of the wheelchair and contributions of gravitational forces on slopes (6). However, the latter does not influence the friction force in WCR since the court is a flat ground without slopes. The air drag is dependent on velocity and thus not considered in *Eq. (1).* The force equation (*Eq. (1))* can only be applied at the wheelchair plus athlete if other forces are also neglected. These other forces are mutual forces between wheelchair and athlete as well as rotational and environmental forces.

Neglecting the above-mentioned forces simplifies the approach to measure the friction force during a standardized coast-down. This simplification can be substantiated. In previous studies it is shown that the air resistance forces contribute little to the total drag force of a wheelchair compared to the rolling resistance at lower velocities (10, 11). Since WCR coast-down test are performed indoor and the velocities are relatively low, it can be assumed that the air drag contributes little to the total friction force and thus the velocity dependent factor may be neglected. During a standardized coast-down, the athlete does not propel the wheelchair and moves as little as possible, thus mutual forces between wheelchair and athlete influencing the deceleration in the driving direction are minimal. Hence, the wheelchair plus athlete can be assumed as rigid body in the simplified approach. A standardized coast-down is ideally performed linearly. The effect of rotational forces is assumed to be minimal during those tests. Likewise, the effect of environmental forces, since, in principle, no contact occurs between the wheelchair and other players or objects during a standardized coast-down.

If the assumptions around neglecting forces are correct, the friction forces could be determined during any moment of linear deceleration in a WCR match-setting and not only during standardized coast-downs. Two other types of linear deceleration periods are non-standardized coasting and the recovery phases during a sprint. The non-standardized coast-down is similar to the standardized coast-down, but the deceleration is performed on the athlete's initiative in a non-controlled setting during a field test, training or match. The deceleration period of a standardized coast-down is determined retrospectively based on kinematic data. The sprint deceleration can be found during a linear sprint, the wheelchair is propelled by consecutive push cycles. During each push cycle there is a propulsion phase in which the athlete propels the rim and a recovery phase in which the hands move back for a new propulsion (12). During the recovery phase no propulsion occurs, and the wheelchair decelerates. The deceleration during the recovery phase is referred to as sprint deceleration.

If friction forces can be determined based on IMU-data during different types of linear deceleration in WCR field data, the first step is made to determine friction forces in WCR match-setting. However, the method of determining friction forces with the use of IMUs has not yet been proven in practice for WCR.

This study aimed, therefore, to explore whether friction forces can be determined based on IMU-data in WCR field. Three types of linear deceleration periods were studied: standardized coast-down, non-standardized coast-down and a sprint deceleration. The effects of velocity, frame rotation, trunk movement, mass of wheelchair plus athlete and classification score on the deceleration were studied to verify the made assumptions and declare possible deviations in decelerations. The standardized coast down deceleration formed the golden standard to compare with the other two types of decelerations. It was hypothesized that the deceleration values during the non-standardized coast-down and sprint deceleration would correspond to the deceleration values of the standardized coast-down. Higher trunk movement and mass were expected to be related to deceleration.

Materials & methods

The data set used in for this study was received from Dr. R.M.A. van der Slikke. In the following section a description is given of the materials and methods used for the collection of the data.

Study population

For this study, data collected at the Wheelchair Rugby World Championships in Vejle, Denmark. The study was conducted from Oct. 10 to Oct. 16, 2022. 21 professional WCR players participated in this study. Due to measurement errors, two participants were excluded for this study. The characteristics of the nineteen included participants can be found in *Table 1*. All participants gave written consent.

Table 1: Participant characteristics

Athlete characteristics	N or mean (std)
Male/Female (n)	16/3
Mass (kg)	66.89 (8.61)
Classification score	2.24 (0.89)
Wheelchair characteristics	
Wheel diameter (inch)	24.1 (0.23)
Track width (m)	0.79 (0.04)
Camber (deg)	18 (1.25)
Mass (kg)	19.16 (1.84)

Study design

Each subject performed a field test on the wheelchair rugby court. The test took around 10 minutes for every subject. If a part of the test was not performed as wished, that part was retaken, and an annotation was made.

The field test consisted of the following items:

1. 20-meter sprint
2. 12-meter sprint with full stop
3. An intermittent sprint: 3-meter sprint, stop, 3-meter sprint, stop, 6-meter sprint with full stop
4. Sprint-curve-slalom-curve (see *Figure 1*)
5. Turn on the spot 180 degrees, once to the right and once to the left.
6. Turn on the spot 90 degrees, stop, turn 90 degrees in the same direction, once to the right and once to the left
7. X-figure run test, four times (see *Figure 1*)
8. Coast-down, three times

The study was approved by the ethical committee of TU Delft.

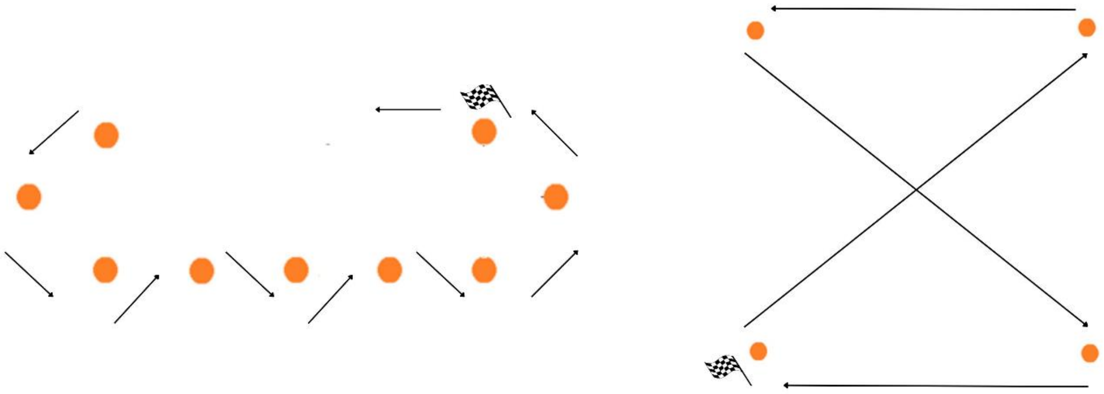

Figure 1: Illustrations of the sprint-curve-slalom-curve test (left) and the x-figure run (right)

Equipment

To measure the kinematics of the athlete and the wheelchair during the field test, three IMU-sensors (Movesense Active®) were used. One sensor was placed in the right wheel of the wheelchair and one on the frame as can be seen in *Figure 2.* This set-up is found to be reliable to measure linear wheelchair velocity and frame rotations at lower velocities (9, 13). The third sensor was placed on the front of the trunk of the athlete with a heart-rate belt. The IMU-sensors determined linear accelerations, angular velocities and strength and direction of the local magnetic fields in three dimensions. The sample frequency (fs) of IMUs was set on 100 Hz. The software used to receive the IMU-data was an app from Kaasa®.

Every participant performed the field test in his or her personal sports wheelchair. For every wheelchair, the wheel diameter, track width (distance between the rear wheels at ground level) and camber (angle between rear wheel and vertical) were measured. The mean values for these variables can be found in *Table 1*.

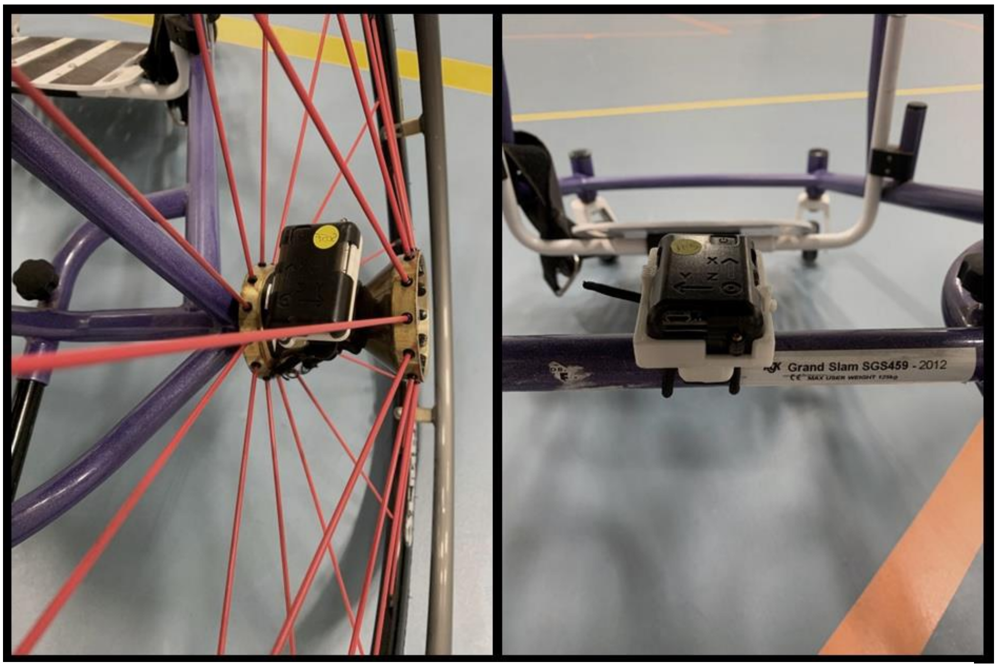

Figure 2: Placement of sensor right wheel (left picture) and on frame (right picture)

Data selection

Standardized coast-down

The three standardized coast-downs were performed at the end of the field test. If one or more coast-downs were not properly executed, a fourth coast-down was performed. This happened for example if too much frame rotation occurred or when a participant used his/her arms excessively for steering or braking. The participants performed the field test at their own preferred speed. Although every participant completed the coast-downs as the last item of the test, the exact starting time and end time of the coast-downs differed among the subjects. To make sure the right part of the signal was analyzed, the coast-downs were selected by hand. The forward velocity of the wheelchair and the frame rotation were plotted in the same figure against the time with a normalized y-axis. For each coast-down, the start of the deceleration period was chosen based on two conditions; the forward wheelchair velocity signal should be flattened after the spikes of the push phases and the frame rotation signal should be around zero. The end of the deceleration period was set at the point where the forward wheelchair velocity and/or the frame rotation began to increase. An example of this selection method can be found in *Figure 14* in *Appendix 1.*

After determination of the deceleration period, the mean values of four variables were calculated over the selected period. These variables were:

1. $mean\_a_{frame}$ = the mean deceleration of the frame, based on $\frac{dv_{frame}}{dt}$ over the selected deceleration period
2. $mean\_v_{frame}$ = the mean velocity of the frame over the selected deceleration period
3. $mean\_\omega_{frame}$ = the mean rotational speed of the frame over the selected deceleration period
4. $mean\_abs\_\omega_{trunk}$ = the mean of the absolute rotational speed values of the trunk over the selected deceleration period. The absolute values were taken to prevent positive values canceled out by negative values or the other way around.

Non-standardized coast-down

As mentioned in the *Introduction* non-standardized coast-downs are similar to standardized coast-downs but performed on the athlete's initiative in a non-controlled setting. The non-standardized coast-down deceleration phases were selected during the data analysis based on five criteria. To minimize the effect of rotational forces, the non-standardized coast-downs were selected based on low rotational frame speeds. To minimize the effect of mutual forces between athlete and wheelchair, the non-standardized coast-downs were selected based on low trunk movement. To exclude phases were braking occurred, a maximum value for deceleration was set to find non-standardized coast-downs. Before a standardized coast-down, an athlete propels the wheelchair, an initial velocity threshold was thus imposed to select non-standardized coast-downs. To reduce measurement errors, the deceleration phase of the non-standardized coast-downs had to contain enough samples.

The five conditions for the non-standardized coast-downs were specified as follows:

1. During the deceleration phase, the frame rotational speed should be between -10 deg/s and + 10 deg/s
2. During the deceleration phase, the mean absolute trunk rotational speed should be below 10 deg/s
3. The deceleration phase should have a mean deceleration between -0.05 m/s^2 and -0.45 m/s^2
4. During the deceleration phase, the mean velocity should be above 0.5 m/s
5. The deceleration phase should have at least a length of one hundred samples (1 second)

For each non-standardized coast down deceleration phase, the four variables mentioned in *Standardized coast-down* were calculated.

Sprint

The field test started with a 20m sprint. This sprint was selected in the forward frame velocity signal by hand for each participant. With the function 'findpeaks' in Matlab the first ten pushes were selected. The phase between the highest point in the forward frame velocity and the lowest point was marked as the recovery phase, an example is shown in *Figure 15* in *Appendix 1.* For the recovery phases in the sprint, the four variables mentioned in *Standardized coast-down* were calculated.

Signal analysis

Gyroscope signals from the IMU-sensors placed on wheel, frame and trunk were imported and derived in MATLAB (R2022a, The Mathworks Inc.). The gyroscope signals were saved as angular velocities in degrees per second. For each IMU sensor, wheel, frame and trunk, the angular velocities around x-, y- and z-axis were available. The angular velocities from the wheel sensor and the frame sensor were used to derive the frame speed of the wheelchair using the following equations based on van Dijk et al. (13):

Firstly, the rotational speed of the frame (ω_{frame}) was corrected for possible misalignment.

$$\omega_{frame} = sgn(\omega_{frame,z}) \cdot \sqrt{\omega_{frame,z}^2 + \omega_{frame,y}^2} \qquad \textit{Eq.(2)}$$

Secondly, the angular velocity of the wheel (ω_{wheel}) was calculated based on the rotational speed of the wheel and corrected for the camber angle of the rear wheel.

$$\omega_{wheel} = \omega_{wheel} - \tan \varphi_{camber} \cdot \omega_{frame} \cdot \cos \varphi_{camber} \qquad \textit{Eq. (3)}$$

Thirdly, the forward velocity of the wheel (V_{wheel}) was calculated based on the angular velocity of the wheel and the wheel circumference.

$$V_{wheel} = \omega_{wheel} \cdot (\emptyset_{wheel} \cdot \frac{\pi}{360}) \qquad \textit{Eq. (4)}$$

Fourthly, the forward velocity of the frame was derived from the wheel velocity with corrections for frame rotation and the distance between the wheel axis and the frame center.

$$V_{frame} = V_{wheel} + (tan(\frac{\omega_{frame}}{fs}) \cdot \frac{trackwidth}{2}) \cdot fs \qquad \text{Eq. (5)}$$

In *Eq. (5)* $trackwidth$ stands for the distance between the rear wheels at ground level. The sample frequency is referred to as fs.

The forward trunk movement was based on the trunk movement around the transversal axis of the trunk, which was the gyroscope signal of the x-axis of the trunk sensor. For all three gyroscope signals, the offset was removed by subtraction of the mean values and the signals were filtered with a second order low-pass butter filter with a cut-off frequency of 10 Hz.

Statistical analysis

After data processing, statistical analysis was performed in SPSS Statistics version 26 (IBM SPSS, Armonk, NY, USA).

Test-retest reliability standardized coast-down

The quality of the repeated standardized coast-down trials was assessed with two Intraclass Correlation analyses. One for the subjects who performed three standardized coast-downs (N = 14) and one for the subjects who performed four standardized coast-downs (N = 5). Two-way Mixed models were chosen to see if the repeated coast-downs within subjects resembled each other. The model type was set as 'Absolute Agreement,' and the single measures ICCs were interpreted. The Intraclass Correlation Coefficients (ICCs) were interpreted based on their 95% confidence intervals (CIs) as shown in *Table 2*.

Table 2: Interpretation of the Intraclass Correlation Coefficients (ICCs) according to Koo and Li (14)

Intraclass Correlation Coefficient	Interpretation
1.00 – 0.90	Excellent agreement
0.75 – 0.90	Good agreement
0.50 – 0.75	Moderate agreement
< 0.50	Poor agreement

Generalized estimating equations

To find the effects of velocity, frame rotation, trunk movement, mass and classification score on deceleration, three types of GEEs (Generalized Estimating Equations) were performed for each deceleration type. So, in total nine models were implemented. A GEE design was chosen since each subject has multiple deceleration measurements and different subjects were compared to each other. The chosen structure corrects for the within-subject factors. For all three models, the correlation structure was set as Exchangeable, the model type was set as Linear Scale response and model effects were analyzed using Type III. The deceleration value was set as the dependent variable and the subject number was used as subject variable in all the models.

In the first model, velocity, frame rotation and trunk movement were set as within-subject variables to correct the outcome for repeated measures. Velocity, frame rotation, absolute trunk movement, mass and classification score were set as predictors. The first model had the most predictors, the second and third model were simplified versions, to find out whether the variables had mutual effects.

The second model left out mass and classification score as predictors. Mean velocity, mean frame rotation and mean absolute trunk movement were set as within-subject variables and as predictors. Hence, the second model left out the factors that are constant within subjects.

The third model included velocity as within-subject variable. Velocity, mass and classification score were set as predictors. Frame rotation and absolute trunk movement were left out of the third model since these variables were imposed to find non-standardized coast-down deceleration values.

Factors in the model with a p-value below 0.05 were considered to have a significant relation with the dependent variable deceleration.

Comparisons between deceleration types

Two Intraclass Correlation analyses were conducted to assess the agreement between the deceleration types. One analysis was executed to find the agreement between standardized coast-down deceleration and non-standardized coast-down deceleration and one to find the agreement between standardized coast-down deceleration and sprint deceleration. Two-Way Mixed models were chosen to see if the different methods led to the same deceleration values per subject. Since the decelerations were determined in different ways, the model type was set as ‘Consistency’. The ICCs for average measures were interpreted since the average deceleration per subject is analyzed. The Intraclass Correlation Coefficients (ICCs) were interpreted based on their 95% confidence intervals (CIs) as shown in *Table 2*.

Results

Standardized coast-down

To visualize the spread of mean deceleration values within and between subjects during standardized coast-downs, a scatterplot is shown in *Figure 3.* Fourteen subjects performed three coast-down tests, the other five participants performed four coast-down tests, which led to a total of 62 standardized coast-down deceleration values.

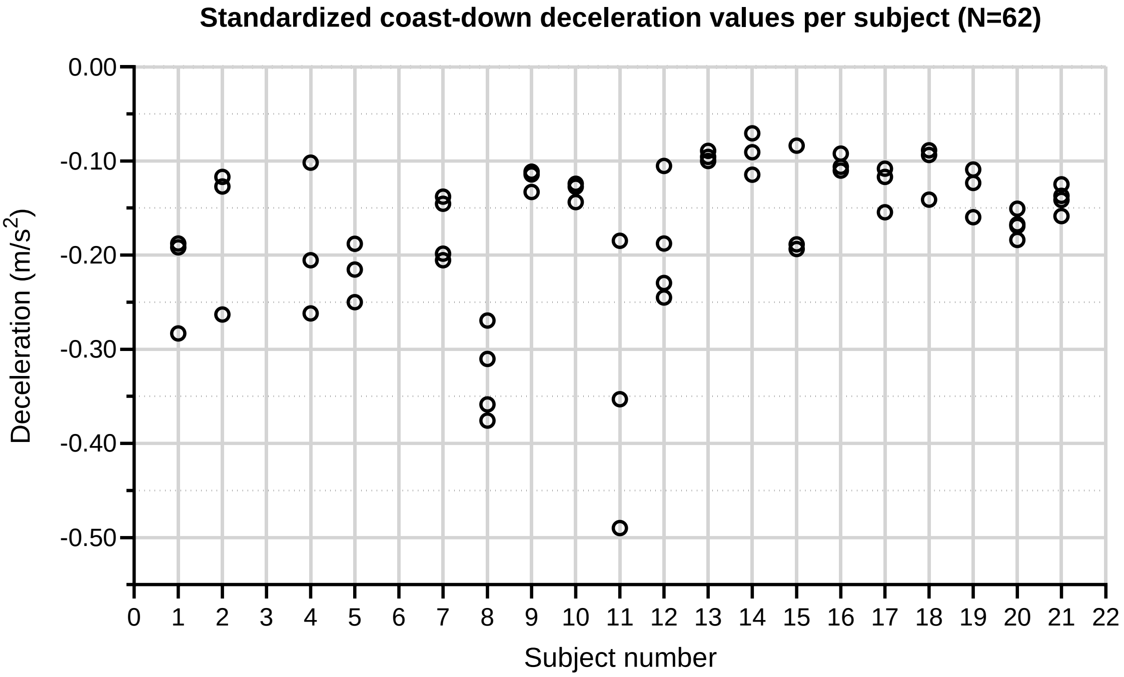

Figure 3: Standardized coast-down deceleration values per subject

The standardized coast-down deceleration values showed a poor to good agreement for the subjects who performed three standardized coast-downs (ICC = 0.507, 95% CI [0.180, 0.782]). For the subjects who performed four standardized coast-downs, the standardized coast-down deceleration values showed a poor to excellent agreement (ICC = 0.768, 95% CI [0.406, 0.968]).

Ideally, if a coast-down was performed under the same circumstances, it would lead to approximately the same deceleration value within a subject. A good to excellent agreement between the deceleration values within subjects was therefore expected. For some subjects (e.g., 9, 13 and 16) this was true, as can be seen in *Figure 3*. For other subjects (e.g., 4, 11 and 15) the deceleration values were spread widely. It is thus questionable if the standardized coast-down can be used as a golden standard for all the subjects.

The deceleration values were also spread between subjects. Minor differences were expected due to variations in mass and wheelchair alignment. However, the spread of deceleration values of the standardized coast-down was larger than expected.

Velocity, frame rotation, trunk movement, mass and classification score were studied by means of three GEEs to see whether the variables can explain deviations in deceleration values of the standardized coast-downs.

In model 1, no significant relation with deceleration was found for velocity (B(1) = -0.013, p = 0.407), frame rotational speed (B(1) = 0.001, p = 0.467), absolute trunk movement (B(1) = 3.885E-5, p = 0.842), mass (B(1) = -0.003, p = 0.081) and classification score (B(1) = -0.025, p = 0.080).

In model 2, a significant relation with deceleration was found for velocity (B(1) = -0.029, p = 0.019), no significant relation with deceleration was found for frame rotational speed (B(1) = 0.001, p = 0.434) and absolute trunk movement (B(1) = 0.000, p = 0.067).

In model 3, no significant relation with deceleration was found for velocity (B(1) = -0.012, p = 0.441), mass (B(1) = -0.003, p = 0.069) and classification score (B(1) = -0.025, p = 0.075).

The results of the three GEEs regarding standardized coast-downs can also be found in *Table 4* in *Appendix 2.*

Figure 4 shows the relation between velocity and deceleration. A higher velocity seems to be related to a higher deceleration, although the r-squared of the fit line is low. The trend between velocity and deceleration was substantiated by the significant relation found in Model 2, where mass and classification score were left out. Hence, a higher velocity might be related to a higher deceleration, but the relationship was weak and ruled out easily when other factors were considered. Velocity might be related to mass and classification score since these factors influence the effect of velocity.

Frame rotation was not found to be significantly related to standardized coast-down deceleration in any of the models. This was expected since the coast-downs are, in principle, performed linearly. The blue markers of *Figure 5* visualize the frame rotation. Most of the values were found between -5 and +5 deg/s, which suggests the coast-downs were performed almost linearly. It was intended to select the standardized coast-down periods based on a flattened frame rotation signal (see methods - *Standardized coast-down*). For most subjects, the frame rotational values were low (*Figure 5*) and thus the selection of the period did go as intended. For the subjects 5 and 11 the frame rotation was found to be -10.3 and 6.8 deg/s, respectively. For these subjects, the selection could have been more accurate, although the values of frame rotation are still acceptable.

The red markers in *Figure 5* show that eighteen standardized coast-downs were performed with an absolute trunk movement below 20 deg/s. Subject number 10 had absolute trunk movements ranging from 62.02 to 130.61 deg/s. This subject might have tried to steer with his/her trunk during the coast-down which caused the trunk movement, or the IMU at the trunk did not function as supposed. The other subjects managed to perform the standardized coast-down correctly regarding trunk movement. It was expected that absolute trunk movement would not be significantly related to deceleration during the standardized coast-down since ideally no trunk movement occurred during this type of deceleration.

Mass and classification score were not found to be significantly related to deceleration, although they nearly reached significance in model 1 and 3. It was expected that a higher mass would be related to a higher deceleration, since a higher mass would lead to a higher normal force and thus a higher rolling resistance.

Hence, velocity, frame rotation, absolute trunk movement, mass and classification score cannot explain the deviations in decelerations during the standardized coast-downs.

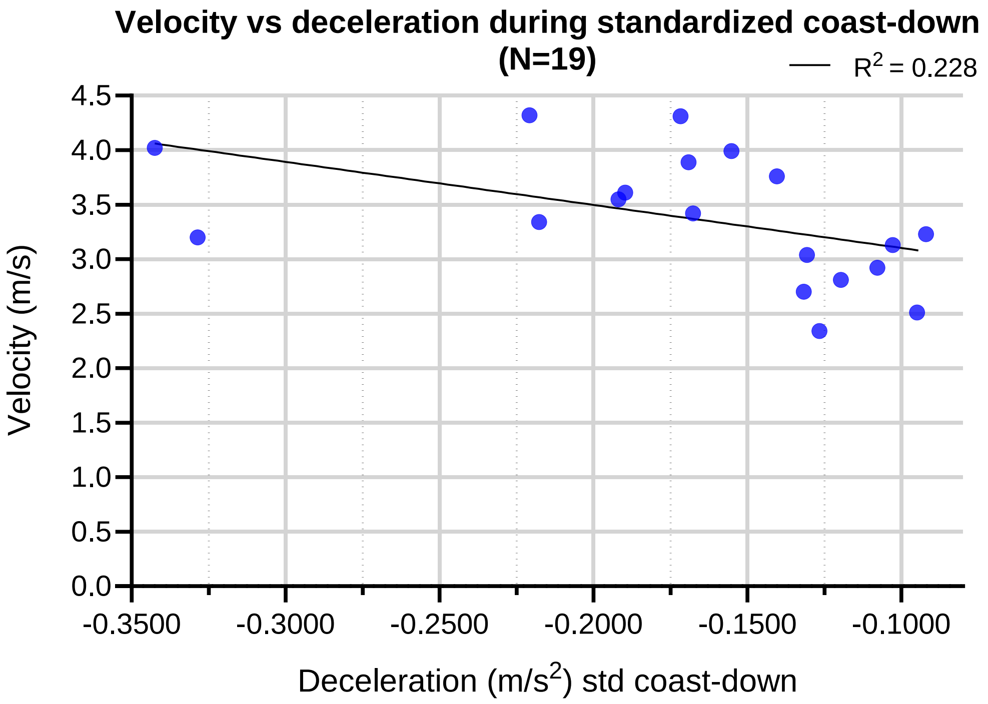

Figure 4: Visualization of the relation between standardized coast-down deceleration and wheelchair velocity

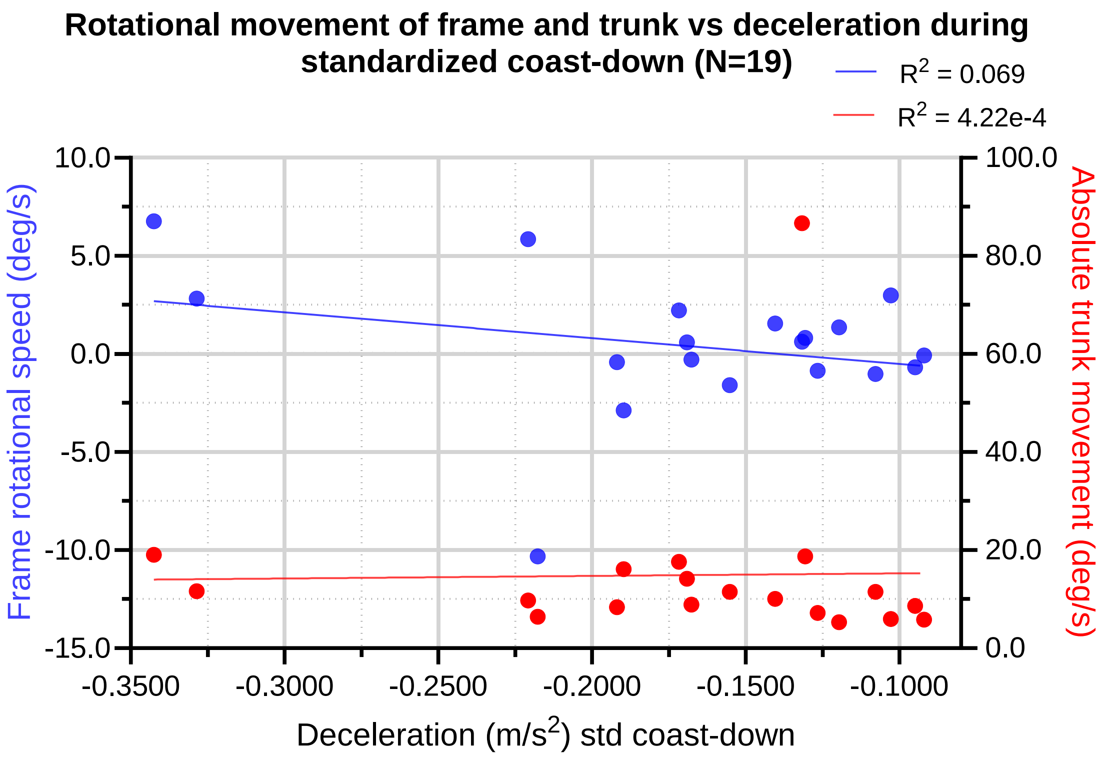

Figure 5: Visualization of the relations between standardized coast-down deceleration and frame rotation (blue) and trunk movement (red)

Non-standardized coast-down

For each of the nineteen subject at least one deceleration value complied with the requirements mentioned in *Non-standardized coast-down.* A total of 71 deceleration values was found, with a maximum of seven values per subject. The spread of values is visualized in *Figure 6*.

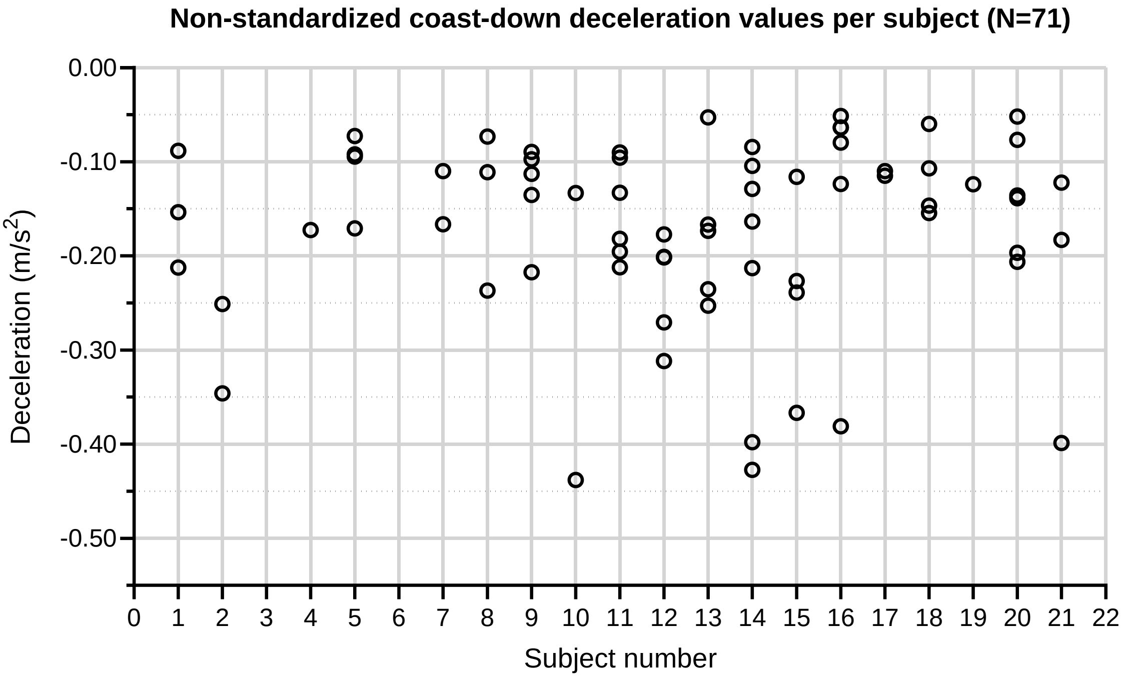

Figure 6: Non-standardized coast-down deceleration values per subject

Velocity, frame rotation, trunk movement, mass and classification score were studied by means of three GEEs to see whether the variables can explain deviations in deceleration values of the standardized coast-downs.

In model 1, no significant relation with deceleration was found for velocity (B(1) = -0.006, p = 0.706), frame rotational speed (B(1) = 0.004, p = 0.058), absolute trunk movement (B(1) = -0.006, p = 0.153), mass (B(1) = -0.002, p = 0.219) and classification score (B(1) = 0.007, p = 0.648).

In model 2, no significant relation with deceleration was found for velocity (B(1) = -0.007, p = 0.625), frame rotational speed (B(1) = 0.004, p = 0.054) and absolute trunk movement (B(1) = -0.008, p = 0.073).

In model 3, no significant relation with deceleration was found for velocity (B(1) = -0.005, p = 0.757), mass (B(1) = -0.002, p = 0.177) and classification score (B(1) = 0.008, p = 0.559).

The results of the three GEEs regarding non-standardized coast-downs can also be found in *Table 5* in *Appendix 2.*

No significant relationship was found between non-standardized coast-down deceleration and velocity in any of the models. *Figure 7* visualizes the relationship between velocity and non-standardized coast-down deceleration, no trend is visible and the r-squared is low.

Frame rotational speed nearly reached a significant relationship with non-standardized coast-down decelerations in models 1 and 2. The relation between frame rotational speed and standardized coast-down is also visualized in *Figure 8*. The frame rotation values were found between -7 and +5 deg/s. The non-standardized coast-down decelerations were selected based on frame rotation between -10 and +10 deg/s (see methods - *Non-standardized coast-down*), thus these results were expected. Since there was slight variation in frame rotational speeds, no robust relationship between frame rotation and deceleration can be shown based on these data.

Absolute trunk movement nearly reached a significant relationship with deceleration in model 2, but the relationship in model 1 was far from significance. In *Figure 8* the relationship between non-standardized coast-down deceleration and trunk movement is visualized. The trunk movement values were all below 10 deg/s, which was also expected due to the selection of deceleration based on low trunk movements (see methods - *Non-standardized coast-down*). Due to the slight variation in trunk movement, no robust relationship between deceleration and trunk movement can be shown based on these data.

No significant relationships were found between non-standardized coast-down deceleration and mass and classification score. A relationship between mass and non-standardized coast-down deceleration was expected, as in the standardized coast-down analysis, but thus not found.

Consequently, deviations in deceleration values of the non-standardized coast-down values cannot be explained by velocity, frame rotation, absolute trunk movement, mass or classification score.

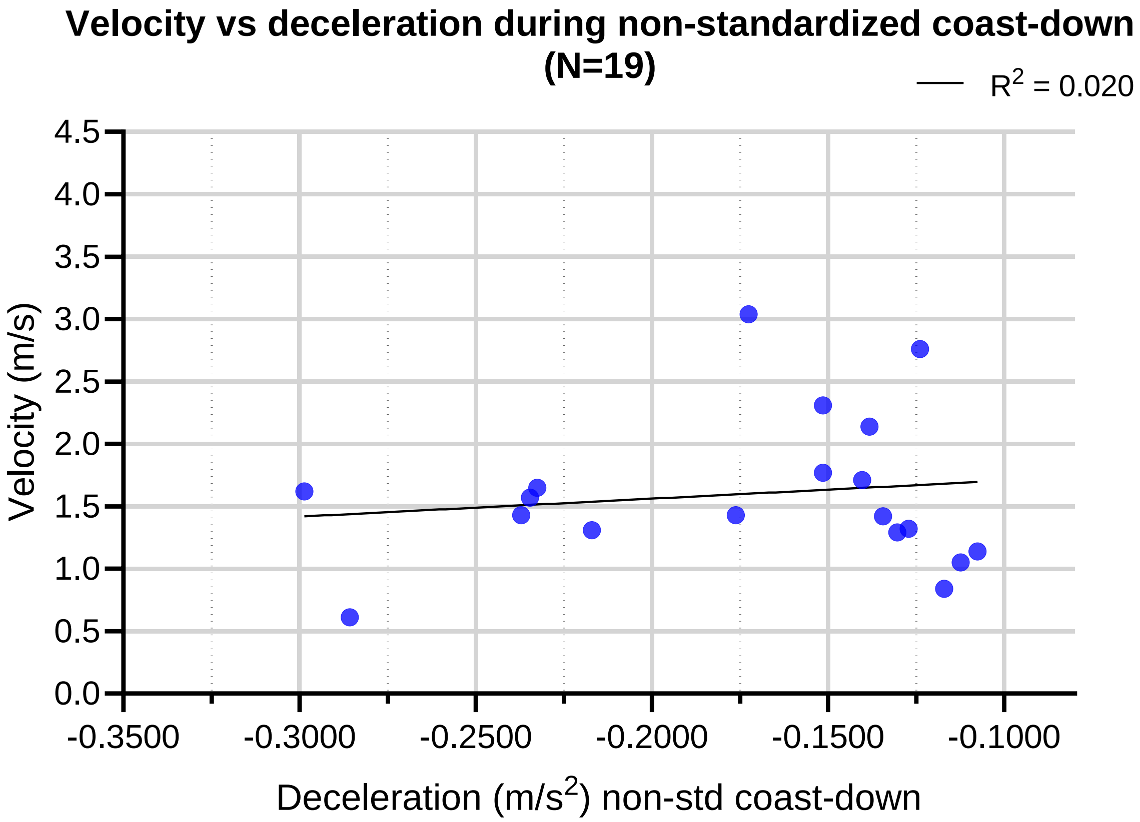

Figure 7: Visualization of the relation between non-standardized coast-down deceleration and wheelchair velocity

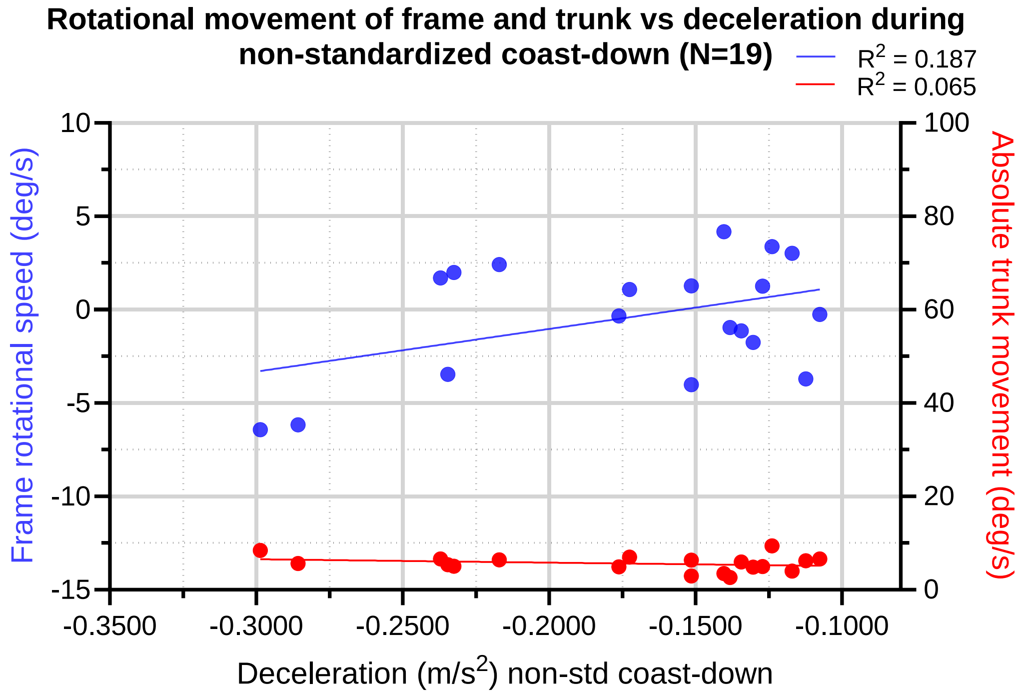

Figure 8: Visualization of the relations between non-standardized coast-down deceleration and frame rotation (blue) and trunk movement (red)

Sprint

In each push, a deceleration phase takes place at the moment no propulsion occurs. In this study, ten pushes in the 20m sprint were analyzed for each subject. For one subject, only nine pushes could be analyzed, which led to a total number of 189 decelerations. The spread of values is visualized in *Figure 9.*

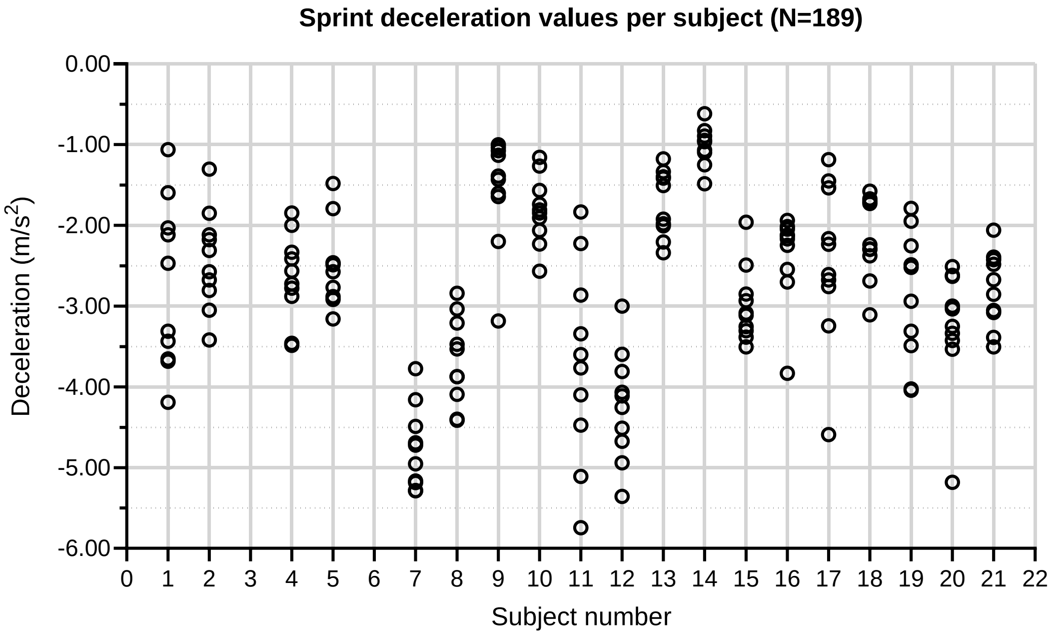

Figure 9: Sprint deceleration values per subject

Velocity, frame rotation, trunk movement, mass and classification score were studied by means of three GEEs to see whether the variables can explain deviations in deceleration values of the 20m sprint.

In model 1, a significant relation with deceleration was found for velocity (B(1) = -0.128, p = 0.027), absolute trunk movement (B(1) = -0.004, p = 0.010) and classification score (B(1) = -0.541 p = 0.011). No significant relation with deceleration was found for frame rotational speed (B(1) = -0.003, p = 0.635) and mass (B(1) = -0.026, p = 0.145).

In model 2, a significant relation with deceleration was found for velocity (B(1) = -0.159, p = 0.004) and absolute trunk movement (B(1) = 0.010, p = -0.005). No significant relation with deceleration was found for frame rotational speed (B(1) = -0.005, p = 0.447).

In model 3, a significant relation with deceleration was found for classification score (B(1) = -0.585, p = 0.003). No significant relation with deceleration was found for velocity (B(1) = -0.125, p = 0.052) and mass (B(1) = -0.027, p = 0.149). The results of the three GEEs regarding sprint decelerations can also be found in *Table 6* in *Appendix 2.*

Velocity was found to have a significant relationship with sprint deceleration in models 1 and 2 and in model 3 the relationship nearly reached significance. *Figure 10* visualizes the relation between velocity and sprint deceleration. The r-squared is relatively high. These results suggest that a higher velocity is related to a higher deceleration during sprint.

Frame rotational speed was not found to have a significant relationship with deceleration. In *Figure 11*, the blue markers represent the frame rotational speed on the left y-axis. Most of the values were found between -10 and +10 deg/s, which suggests that the sprints were performed almost linearly. Due to the little variance in frame rotational speeds, a relation with deceleration was also not expected.

Absolute trunk movement was found to have a significant relationship with sprint deceleration in models 1 and 2. The B-value, however, showed that the relative contribution of trunk movement compared to other variables was low. The red markers in *Figure 11*, represent the absolute trunk movement on the right y-axis. Values up to 250 deg/s occurred. The red fit line suggests that higher trunk movements might be related to higher deceleration values. This supports the significant relationship between absolute trunk movement and sprint deceleration in models 1 and 2. However, the r-squared of the fit line is low in *Figure 11*. A higher trunk movement was expected to be related to a higher deceleration since the athlete exerts more force on the wheelchair compared to low trunk movements.

No significant relation was found between mass and sprint deceleration. As mentioned before, a relation with mass was expected. The relation between mass and deceleration was also not found during the standardized and non-standardized coast-downs.

Classification score has a significant relationship with sprint deceleration in models 1 and 3. According to these models, a higher classification score would lead to a higher deceleration. The relative contribution of the classification score is also large. A relationship of this direction and magnitude between classification score and deceleration was not expected. It was expected that, in general, subjects with a lower classification score would drive the heavier and less agile defensive wheelchairs with higher friction forces. A lower classification score was thus expected to be related to a higher deceleration, contrary to the current results. A higher classification score, however, seems not to be related with a higher wheelchair mass for the current dataset (see *Figure 16* in *Appendix 3)* On the other hand, higher velocity and trunk movement during sprint appear both to be related to a higher classification score (see *Figure 17* and *Figure 18* in *Appendix 3*).

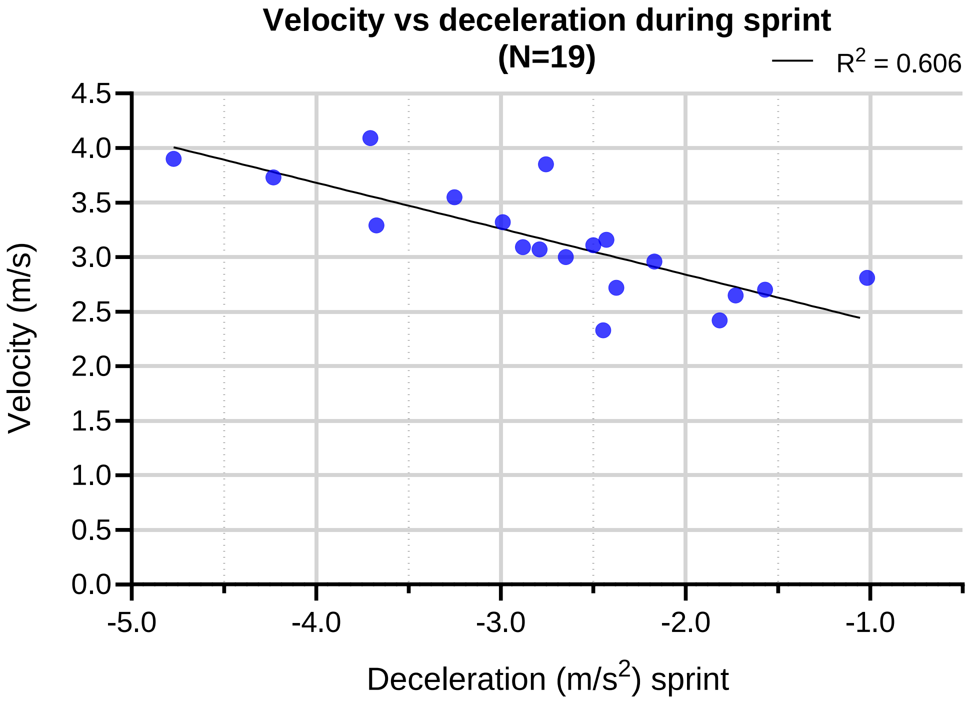

Figure 10: Visualization of the relation between sprint deceleration and wheelchair velocity

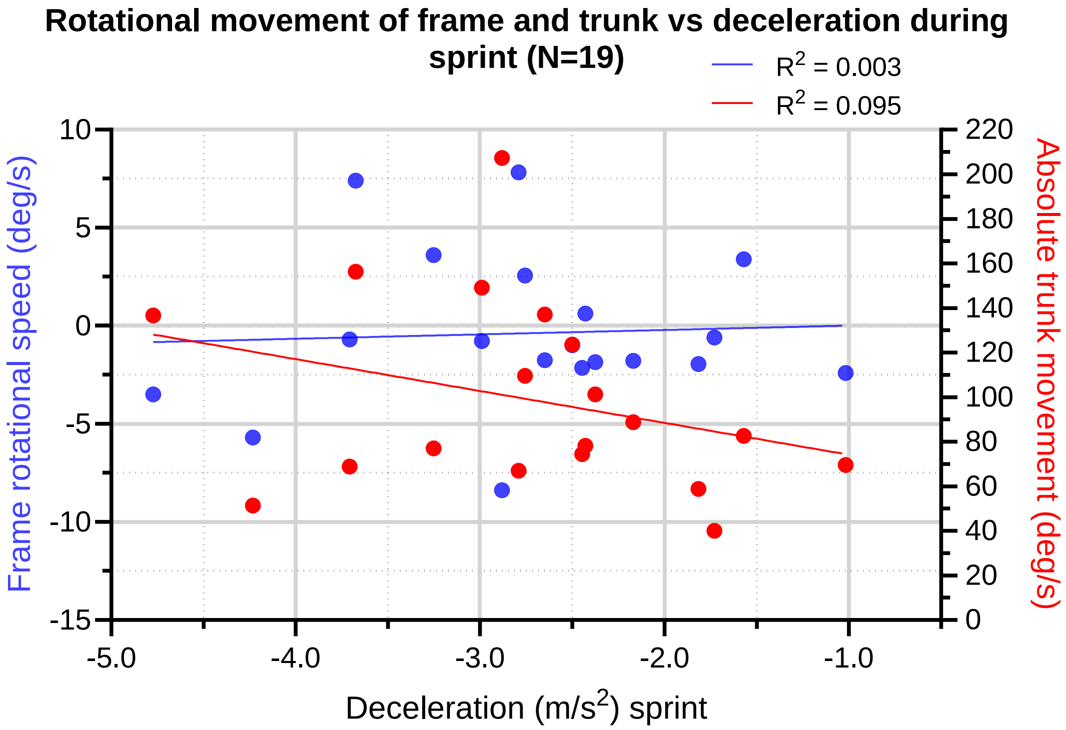

Figure 11: Visualization of the relations between sprint deceleration and wheelchair velocity (top), frame rotation (bottom) and trunk movement (bottom)

Comparisons between deceleration types

In *Table 3* an overview of mean values per deceleration type is given. What stands out is the higher deceleration and trunk movement during the sprint and the lower mean velocity during the non-standardized coast-downs. It should be noted that the mean frame rotation might distort reality, since the mean was taken of positive as well as negative values. The ratio between the mean deceleration values is also visualized in *Figure 12*.

Table 3: Comparison of mean deceleration, velocity, frame rotation and trunk movement per deceleration type.

Deceleration type	Mean deceleration ± std (m/s^2)	Mean velocity ± std (m/s)	Mean frame rotation ± std (deg/s)	Mean absolute trunk movement ± std (deg/s)
Standardized coast-down (N = 62)	-0.1710 ± 0.08	3.40 ± 0.69	0.46 ± 5.95	14.62 ± 18.44
Non-standardized coast-down (N = 71)	-0.1702 ± 0.10	1.48 ± 0.64	0.04 ± 5.37	5.49 ± 2.19
Sprint (N = 189)	-2.7237 ± 0.93	3.15 ± 0.84	-0.36 ± 7.61	98.99 ± 49.32

Std: Standard deviation

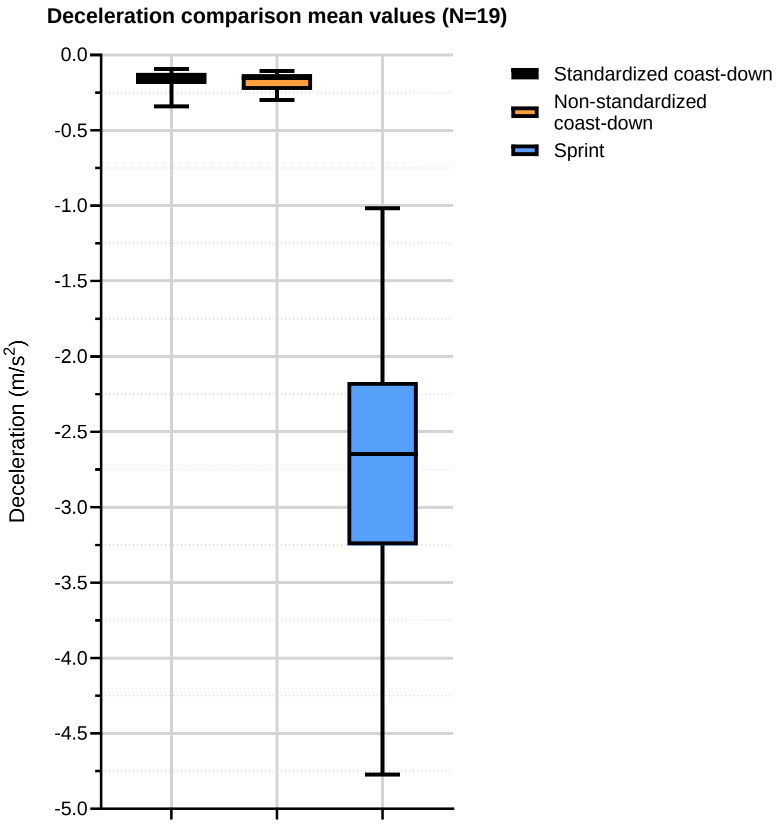

Figure 12: Boxplot visualizing the spread of the three deceleration types averaged for all 19 subjects

To compare the decelerations of standardized coast-down to those of the non-standardized coast-down and sprints, the mean deceleration values per subject per deceleration type were determined. Which led to a number of nineteen deceleration values for each deceleration type.

The mean deceleration values of the non-standardized coast-down showed a poor to moderate agreement with the mean deceleration values of the standardized coast-down (ICC = -0.280, 95% CI [-2.322, 0.507]). The mean deceleration values of the sprint deceleration also showed a poor to moderate agreement with the mean deceleration values of the standardized coast-down (ICC = 0.166, 95% CI [-1.164, 0.679]). Since the largest part of the CIs was below 0.5, the agreement was rather poor than moderate. For both ICCs, the 95% CI consisted of negative values, which indicates the ICC might not be the right measure for the data analyzed.

The (dis)agreements between the deceleration types per subject are shown in *Figure 13*. *Figure 19* in *Appendix 4* shows the scatterplots of each pair of deceleration types. In the case of absolute agreement between two deceleration types, the individual deceleration would be found at the red line crossing the plots. For all three pairs, there was a large deviation between the red line and the line representing the decelerations. Although the ICC results might not reliable, the agreement between the deceleration types was indeed poor, based on the scatterplots.

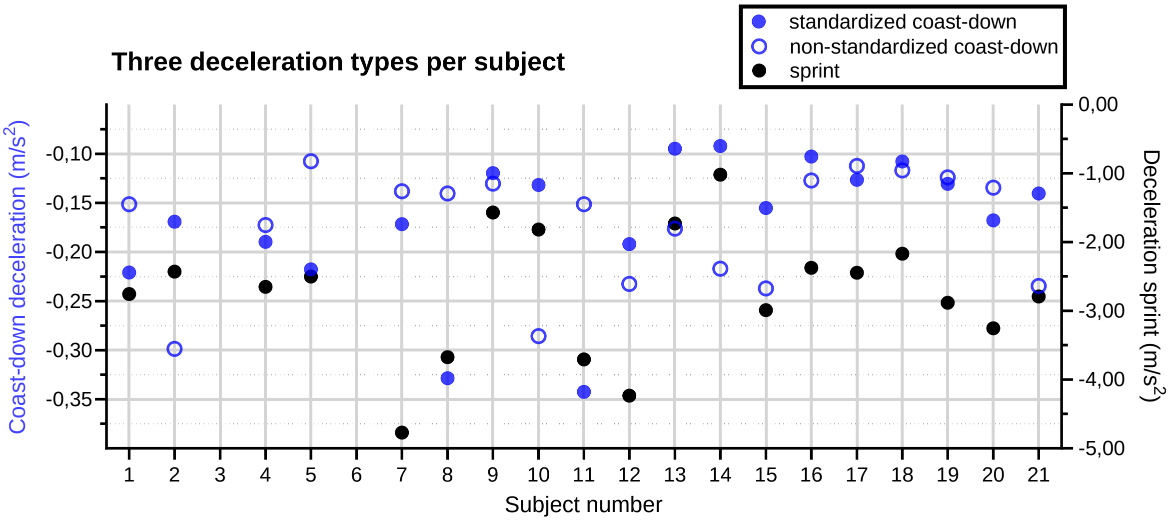

Figure 13: Deceleration values of standardized coast-down, non-standardized coast-down and sprints per subject. The (non)-standardized coast-down values are plotted on the left y-axis and the deceleration values of the sprints on the right y-axis. For each subject, the mean value of each deceleration type is plotted (N = 19)

Discussion

The aim of this study was to determine the friction forces during linear deceleration periods in WCR field from IMU data. Three types of linear deceleration periods were studied, standardized coast-downs, non-standardized coast-downs and sprint decelerations. Since the friction forces were assumed to be linearly dependent on deceleration values of the wheelchair, results focused on deceleration values. It was hypothesized that non-standardized coast-down decelerations and sprint decelerations would resemble the standardized coast down decelerations. Which would prove that friction forces could be determined during different types of linear deceleration periods in WCR field from IMU data. It was additionally hypothesized that a higher deceleration would be related to a higher trunk movement and mass. The results of this study could not substantiate these hypotheses. The agreement between the three deceleration types was poor to moderate. There appears to be a relation between deceleration and the variables velocity, trunk movement and classification score. No significant relation was found between deceleration and the variables frame rotation and mass.

Interpretation

Test-retest reliability standardized coast-down

If the coast-downs would have been performed, measured and analyzed correctly, the spread within subjects would have been smaller than found in this study. Possibly, subjects performed some of the standardized coast-downs with a different trunk angle, which was not analyzed in this study. The center of mass, in that case, is positioned more forward in one coast-down compared to another coast-down. When the trunk is positioned more forward, a larger proportion of the mass is loaded on the castor wheels. The castor wheels encounter more rolling resistance compared to the rear wheels due to the smaller diameter (15). Standardized coast-downs performed under different trunk angles, could thus lead to variance in deceleration values within subjects. Variation in standardized coast-down decelerations within subjects may also have arisen from improper selection of the coast-down period. The deceleration was calculated based on the timespan and the velocity at the start and end of the timespan. If the start and end of the timespan was not set accurately, the deceleration may have been presented higher or lower than. Nevertheless, it was also demonstrated that some subjects had little variance between the standardized coast down decelerations. This shows that it is possible to perform reliable retests of the standardized coast-downs. Previous studies showed that coast-down tests have a good repeatability and can be used to determine decelerations and power estimations (7, 16). Hence, test-retest reliability of standardized coast-downs was expected but could not be strongly evidenced in the current study.

Generalized estimating equations

Velocity

Velocity was found to be significantly related to deceleration in some of the models from the standardized coast-down deceleration and sprint deceleration. This relation was not strongly evidenced. It was assumed in this study that the deceleration would be independent of velocity and air drag was neglected. Several other studies also assumed a linear force-velocity relationship for WCR and wheelchair basketball players (17-19). However, the relation between friction force and velocity is more complex. It is shown that the rolling resistance in wheelchairs can be velocity dependent (20, 21). In addition, the air drag, which is also velocity dependent, might have a larger contribution than expected. Barbosa et al. studied the relative contributions of the velocity independent rolling resistance and the velocity dependent air drag to the total friction force in wheelchair racers (22). They explained the total friction force by the contribution of air drag for about 10% and by the rolling resistance for about 90% at velocities around 3.5 m/s, which is the highest mean velocity found in the current study (*Table 3*). Racing wheelchairs with three wheels were found to be more aerodynamic compared to wheelchairs with four wheels (23). Hence, it is possible that the relative contribution of air drag in WCR wheelchairs is larger than the 10% determined in wheelchair racing. So, evidence exist that the relation between friction force and velocity is more complex than assumed in the current study, caused by velocity dependent characteristics of both rolling resistance and air drag. The GEE models in the current study tested only linear relationships between the variables and deceleration. Another type of model might have led to a stronger relationship between velocity and the three deceleration types.

Frame rotation

No significant relationship was found between deceleration and frame rotation in the current study. In principle it was expected that a higher frame rotation would be related to a higher deceleration due to the effect of rotational forces. However, for this study it was expected that only linear decelerations would be analyzed and thus no relation between these variables would be found. It also turned out that nearly all the decelerations examined were performed linearly. Deviations in frame rotations could thus not be significantly linked to deviations in deceleration.

Trunk movement

Absolute trunk movement was significantly related to deceleration during the sprint deceleration, but the found relationship was weak. Throughout the standardized and non-standardized coast-downs, trunk movement was low, it is thus comprehensible that this variable could not be linked to outliers in deceleration values for these two deceleration types. During the sprint deceleration, the trunk movement was considerably higher compared to the coast-downs. It was expected that higher trunk movement would be related to higher deceleration values, since the athlete exerts forces on the wheelchair that cause the wheelchair to decelerate. However, this relation was not strongly evidenced in the current study. A possible explanation might be found in the double-sided effect of trunk movement on deceleration. On the one hand, the trunk movement can thus cause forces that increase the deceleration of the wheelchair. On the other hand, the trunk extends during a recovery phase (24). The center of mass is moving backwards during this extension. The loading on the castor wheels reduces and a larger part of mass is loaded on the rear wheels. As mentioned before, the rear wheels encounter a lower friction force compared to the castor wheels due to the larger diameter (15). The changing mass distribution caused by trunk extension thus decreases the deceleration of the wheelchair. Since the backwards trunk movement during a recovery phase can as well increase as decrease the deceleration of the wheelchair, it is possible that the relation between trunk movement and deceleration is harder to substantiate than expected. To the authors' knowledge, no studies investigated the balance between the increasing and decreasing effect of trunk movement on deceleration during the recovery phase. So, the type of relationship between the friction force and trunk movement cannot yet estimated. It is certain however, that the trunk movement has a larger increasing effect on deceleration than a decreasing effect. Another possibility for not finding a relation between sprint deceleration and trunk movement could be found in the selection of the recovery phase. In this study, the highest and the lowest peak in the velocity signal were selected to mark the recovery phase. If the recovery phase was not selected properly, a part of the propulsion phase could have been included which reduces the deceleration. Since the trunk movement was analyzed as an absolute value, trunk movement during the part of the propulsion phase could have been added to the movement during the recovery phase. If the recovery phase was defined improper, the deceleration falls lower and the trunk movement higher, which distorts the actual relation between the two variables.

Mass

A relation between mass and deceleration was expected for all three deceleration types, since rolling resistance can be calculated based on the ground reaction forces on the rear and castor wheels (25). However, the relation between mass and deceleration was not found in the current study. Since the relation between mass and deceleration is almost certainly present, there were probably measurement errors in one or both variables. The mass of the wheelchairs was measured on the same scale for all subjects. This can at most have led to overestimation or underestimation of weight if the scale was not calibrated correctly but probably no inter-rater variance occurred. The mass of the athlete was measured on different scales, thus variance could have occurred in these values, but large deviations are not expected. It is thus more likely that errors were made in the measurements of the decelerations. Possible measurement errors in decelerations are discussed in *Test-retest reliability standardized coast-down* for the method of the standardized coast-downs and in *Comparisons between deceleration types* for the non-standardized coast-downs and sprint decelerations.

Classification score

It was expected that a lower classification score would be related to a higher deceleration value. However, this study showed the opposite result, a higher classification score was related to a higher deceleration value. The expectation was based on the assumption that LP-players would drive heavier, and less agile wheelchairs compared to HP-players. For this dataset that was not true, the mass of the wheelchair was not related to classification score. HP-players, however, performed the sprints at higher velocities and with more trunk movement compared to LP-players. It is possible, that due to the greater range of motion, an HP-player exerts more forces on the wheelchair that results in larger decelerations compared to LP-players.

Comparisons between deceleration types

A poor agreement was found between standardized coast-down deceleration and the other two types of decelerations. Explanation for the poor agreement may in part be found in the quality of the standardized coast-downs discussed in *Test-retest reliability standardized coast-down*.

Another explanation for the poor agreement may be found in the uncontrolled part of the non-standardized coast-down. A non-standardized coast-down is a linear deceleration period without trunk movement, like the standardized coast-down. However, during the standardized coast-down, the subject was instructed to not touch the rims with his/her hands. During the other items of the field test described in *Study design* the subject did not receive this instruction. It may well be that subjects touched the rims during the deceleration periods in the field test. This hand contact could have influenced the non-standardized coast-down deceleration values.

The large variation in mean values of the deceleration types might also form an explanation for the poor agreement between the deceleration types. The deceleration values during the sprint were found to be in a magnitude 15-fold higher compared to the deceleration values of the standardized and non-standardized coast-downs. The spread in deceleration values for the sprint only could not be explained by trunk movement. However, it is plausible that the difference in deceleration values between standardized coast-downs and sprint decelerations could be partly explained by the difference in mean trunk movement between the two deceleration types. With the high mean trunk movement during the sprint deceleration, it was not justified to consider the wheelchair plus athlete as a rigid body. The subject must have exerted force on the wheelchair to move the trunk. This force decelerated the wheelchair and thus distorted the determination of the deceleration caused by friction forces. For the standardized and non-standardized coast-downs the internal forces were probably lower, but also not zero. The assumption of wheelchair plus athlete as a rigid body is a simplification of reality and this might have influenced the deceleration values significantly.

Comparison to current knowledge

Rietveld et al. (8) measured deceleration values in wheelchair tennis players to obtain friction forces with the use of IMU's. The coast-down deceleration values in their study varied between -0.06 and -0.09 m/s^2 on a hardcourt surface. In the current study, the coast-down values varied between -0.07 and -0.49 m/s^2. The higher decelerations found in the current study might be partly explained by the differences in sports wheelchairs. The mean mass of the WCT wheelchairs was 11 ± 0.3 kg and the mean mass of the WCR wheelchairs was 19 ± 1.8 kg. A higher mass is related to a higher rolling resistance (25), although not evidenced in the current study. Next to that, the deceleration period in the study of Rietveld et al. started two seconds after the highest velocity peak and ended two seconds before another change in the velocity signal occurred. It was mentioned that these seconds were left out on purpose to avoid movements of the athlete that might have occurred just after accelerating or before braking. In the current method, those four seconds were not left out, but included in the analysis. The possible movements of the athlete during those moments might have increased the decelerations during the standardized coast-downs.

Rietveld et al. also analyzed decelerations during sprints. On a hardcourt surface, they found a mean deceleration of 4.79 m/s^2, which is higher than the 2.72 m/s^2 found in this study. The recovery phases in the sprints are in both studies selected based on peaks in the velocity signal. In the study of Rietveld et al. three IMU's were placed on the wheelchair, while for this study only two were used. The three IMU configuration seems to be more accurate for analysis at push level (13), as explained in *Limitations.* Rietveld et al. used a polyfit function in Python to determine the best slope of the deceleration phases. For the current study, a simple approach with delta velocity divided by delta time was implemented. If improper selection of the recovery phase took place in the current study, a part of the propulsion phase could have been analyzed as recovery phase, which might have decreased the deceleration values. Because of the more accurate method used in the study of Rietveld et al., it is likely that their results for as well the coast-down decelerations as the sprint decelerations are more reliable than the ones of this study.

To the authors' knowledge, there are no studies published that determined decelerations or friction forces based on IMU sensors in WCR or other court sports in field. Clear results measured in the lab are also not published. Next to that, it is not sure if lab-data can be compared to data measured in the field (26).

Limitations

Measuring decelerations and friction forces in field data is an upcoming research field. Every novel approach has its own weaknesses, as is also true for this study.

First, decelerations could be influenced by contact of the anti-tip wheel on the rear side of the wheelchair with the ground, by hands touching the rims, by arm movements or different trunk positions. These interferences were not possible to detect in the IMU-data.

Second, the analysis of the deceleration during the sprints was done at push level, which has a short time frame. It is advised to use a configuration with three IMU's at the wheelchair to analyze at push level in wheelchair sports (13). A lower number of IMU's would lead to less precise wheelchair kinematics, and especially for short timeframes, precision is crucial. In the current study, two IMU's were placed on the wheelchair. The determination of the recovery phases might thus have been inaccurate.

Third, the sensor on the trunk could be relocated during the test due to fluctuating tension on the trunk muscles. This could have influenced the values of the absolute trunk movement, especially during the sprint decelerations. However, the distance of relocation is minor compared to the complete trunk movement during a recovery phase.

Fourth, it was chosen to perform GEEs and ICC reliability tests even though the population was small, and the data was not normally distributed. The negative values in the ICCs suggest this was indeed not the right measure for the data analyzed. However, other types of correlations also had their disadvantages. Therefore, it was still chosen to proceed with the results of the ICCs.

Fifth, the range for frame rotation in the non-standardized coast-down was set on -10 and +10 deg/s. Most values for frame rotation in the standardized coast-down were found between -5 and +5 deg/s, it could be that the range for frame rotation was set too high for the non-standardized coast-downs. This might have led to higher decelerations in the in the non-standardized coast-downs.

Sixth, a disadvantage of the definition of trunk movement in this method is that no distinction could be made between forward and backward movements since the absolute value is used.

Seventh, a disadvantage of the definition of the frame rotation in this method is that the mean of this variable was not informative since the negative values cancel out the positive ones.

Eighth, in case of the standardized coast-downs, five subjects performed four coast-downs, because at least one of the first three did not went as desired. However, all four coast-downs were analyzed for this thesis, and thus also the one that was not performed correctly. Since, the population used for this thesis is not that large, this might have influenced the results. However, the ICC determined for the subjects with four coast-downs differed not much from the one determined for the subjects with three coast-downs.

Nineth, other factors influencing individual differences in coast-down deceleration values can be misalignment of the wheelchair, tyre pressure, faulty bearings or other chair-related resistance factors. No information for these variables was available and no correction took place.

Implications and future directions

The current study did not provide a solid method to determine friction forces during linear decelerations in WCR field. This dataset is gathered at field-tests and not during game situations. This environment creates a more controlled setting compared to game-data since the subject is told to do certain movements. In addition, the dataset is gathered in a more realistic setting compared to measuring on an ergometer. The results showed that measurements with IMUs in field are sensitive to several distortions. Movements that initially appear similar, like the standardized coast-downs, may show large variance in the determined friction force. At the same time, some standardized coast-downs showed good resemblances. Hence, the use of IMUs still offers prospects to determine friction forces in wheelchair sports. It is, although, important to control or correct for distortions. For some of these distortions, velocity, frame rotation, trunk movement and trunk position, it would be valuable to map out their effects on friction force with direct force measurements. This shall not be easy to implement, but can, for example, be done with force instrumented push-rims or in field drag tests. If the effect of the variables is known, IMU-data can be corrected for the distortions. Other factors, like hands touching the rims, are not unambiguously identifiable in IMU data. The use of video footage could identify those events. Correction is in that case presumably difficult, but deviations might be explained with the extra information from the videos. In mobility performance tests, video footage can also be used to calibrate the signals of the trunk sensor and to define the recovery phases during linear sprints.

The recovery phases could also be examined with the use of three IMUs on the wheelchair and the deceleration during these phases could be better determined with the use of the best fitting line instead of the global approach used in this study.

The relations between friction force and the variables velocity and trunk movement could be approached more accurate with a non-linear model.

However, if the steps above will enable the determination of friction forces during linear deceleration periods, there will still be a problem regarding rotations, ball possession, collisions and braking activities during real games. During those moments, friction forces will be different compared to the linear deceleration periods. Also, wheels, with an IMU attached to it, can be replaced during games in case of flat tires and practice shows that there is no time to replace the IMU at those moments. Hence, research focusing on other ways to determine friction forces in WCR is also desirable.

A possible method is to develop light-weight sensors that can measure propulsion forces in the wheel axis. Comparing the force measurements to synchronized IMU-data in field setting, might give new insights on the interpretation of deceleration values and can form a base for model development.

Conclusion

The goal of this study was to determine friction forces during linear deceleration periods in WCR field from IMU-data. The study gave some valuable insights regarding the difficulties related to measuring in the field. Several factors caused uncertainties in the method.

Decelerations determined during non-standardized coast-downs and recovery phases of a sprint did not resemble the deceleration values of the standardized coast-downs which were used as the gold standard. Deceleration was found to be related to velocity, trunk movement and classification score, however the evidence was not convincing. No relation was found between deceleration and the variables frame rotation and mass. Hence, deviations in decelerations could not be explained by studied variables.

The used methodology in this study is thus not yet feasible to implement in practice. The selection methods of the deceleration periods should be improved. Also, the effect of velocity, mutual forces between wheelchair and athlete, frame rotation and trunk position should be investigated more extensively in field. This knowledge can provide opportunities to correct IMU-data for distortions such that in the future, IMUs can be used to determine friction forces in field.

Unfortunately, wheelchair rugby players cannot yet be advised on how to optimize their mobility performance or power output in the field based on IMU data, but plenty of advice for future research has been found.

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Appendix 1 Examples of data selection

Standardized coast-down

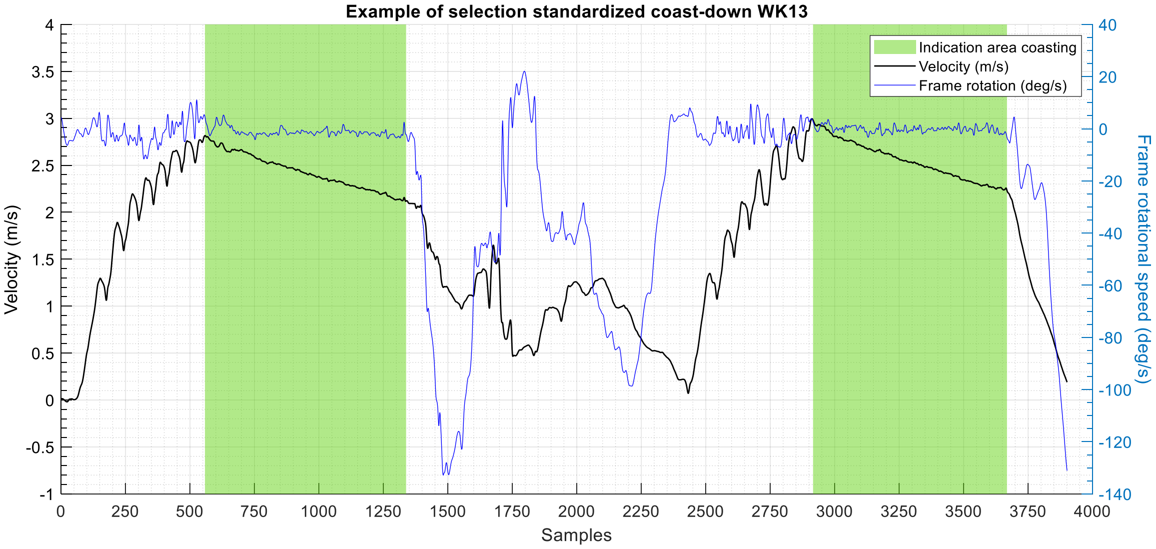


Figure 14: Example of selection standardized coast-down deceleration period. Velocity is represented in the black line on the left y-axis and frame rotational speed is presented in blue line on the right y-axis. Subject is WK 13

Sprint

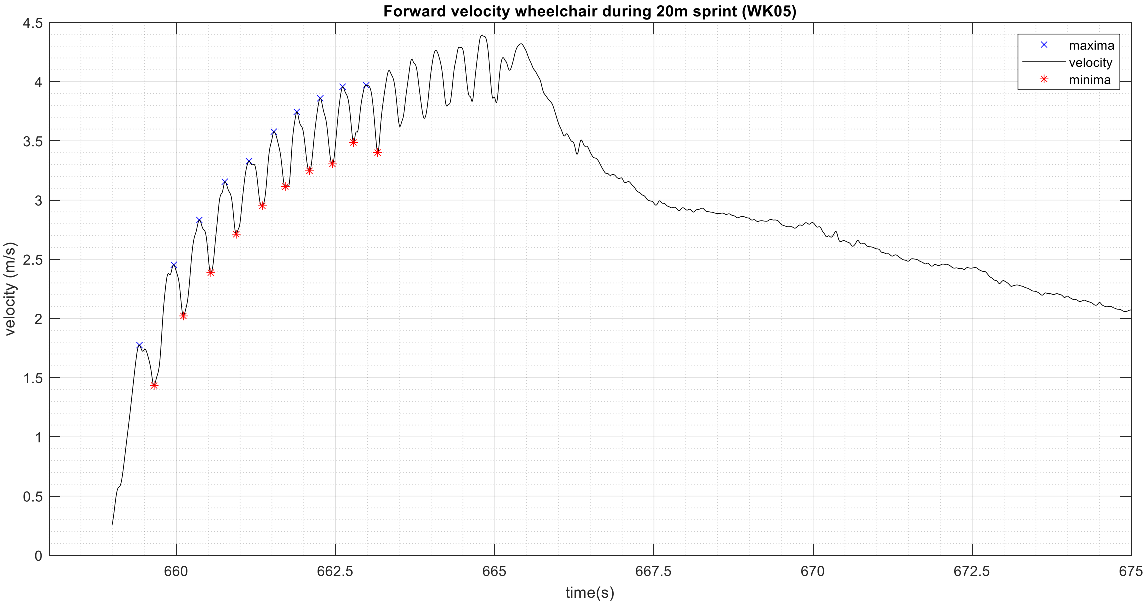


Figure 15: Example of determination sprints from the wheelchair velocity signal. The decelerations between the blue maxima and following red minima are calculated. Subject is WK05

Appendix 2 Results generalized estimating equations

Standardized coast-down

Table 4: Parameter Estimates standardized coast-down (N = 62)

	Model 1		Model 2		Model 3	
Parameter	B(1)	p	B(1)	p	B(1)	p
Velocity (m/s)	-0.013	0.407	-0.029	0.019*	-0.012	0.441
Frame rotational speed (deg/s)	0.001	0.467	0.001	0.434	-	-
Absolute trunk movement (deg/s)	3.885E-5	0.842	0.000	0.067	-	-
Mass (kg) wheelchair + athlete	-0.003	0.081	-	-	-0.003	0.069
Classification score athlete	-0.025	0.080	-	-	-0.025	0.075

Dependent Variable: Deceleration (m/s2) std coast-down

*. Significance at the 0.05 level.

**. Significance at the 0.01 level.

Non-standardized coast-down

Table 5: Parameter Estimates non-standardized coast-down (N = 71)

	Model 1		Model 2		Model 3	
Parameter	B(1)	p	B(1)	p	B(1)	p
Velocity (m/s)	-0.006	0.706	-0.007	0.625	-0.005	0.757
Frame rotational speed (deg/s)	0.004	0.058	0.004	0.054	-	-
Absolute trunk movement (deg/s)	-0.006	0.153	-0.008	0.073	-	-
Mass (kg) wheelchair + athlete	-0.002	0.219	-	-	-0.002	0.177
Classification score athlete	0.007	0.648	-	-	0.008	0.559

Dependent Variable: Deceleration (m/s2) non-std coast-down

*. Significance at the 0.05 level.

**. Significance at the 0.01 level.

Sprint

Table 6: Parameter Estimates sprint (N = 189)

	Model 1		Model 2		Model 3	
Parameter	B(1)	p	B(1)	p	B(1)	p
Velocity (m/s)	-0.128	0.027*	-0.159	0.004**	-0.125	0.052
Frame rotational speed (deg/s)	-0.003	0.635	-0.005	0.447	-	-
Absolute trunk movement (deg/s)	-0.004	0.010*	-0.005	0.006**	-	-
Mass (kg) wheelchair + athlete	-0.026	0.145	-	-	-0.027	0.149
Classification score athlete	-0.541	0.011*	-	-	-0.585	0.003*

Dependent Variable: Deceleration (m/s2) sprint

*. Significance at the 0.05 level.

**. Significance at the 0.01 level.

Appendix 3 Classification score

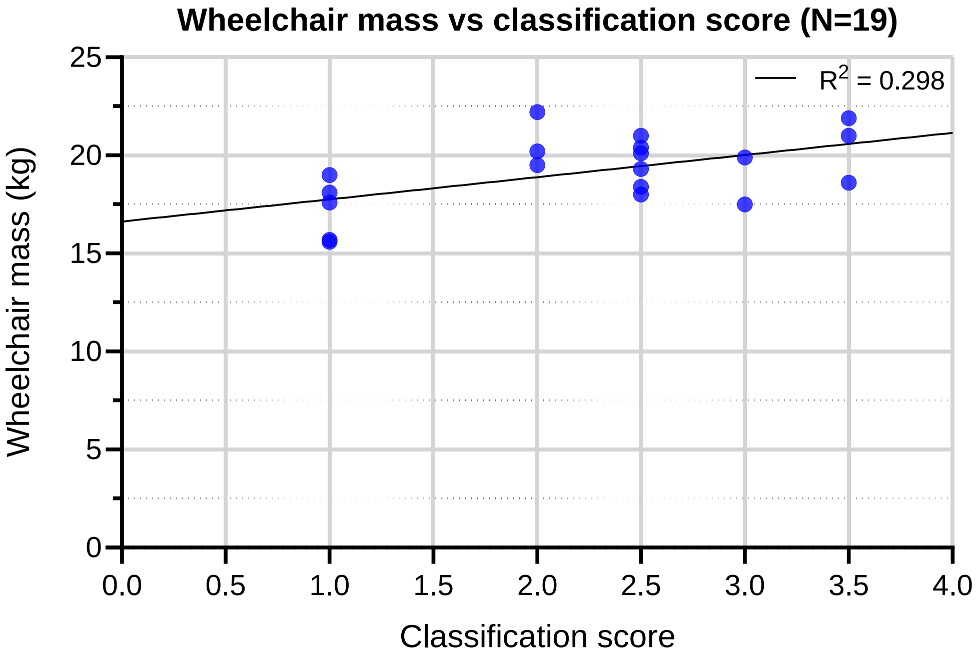


Figure 16: Scatterplot visualizing the relation between wheelchair mass and classification score

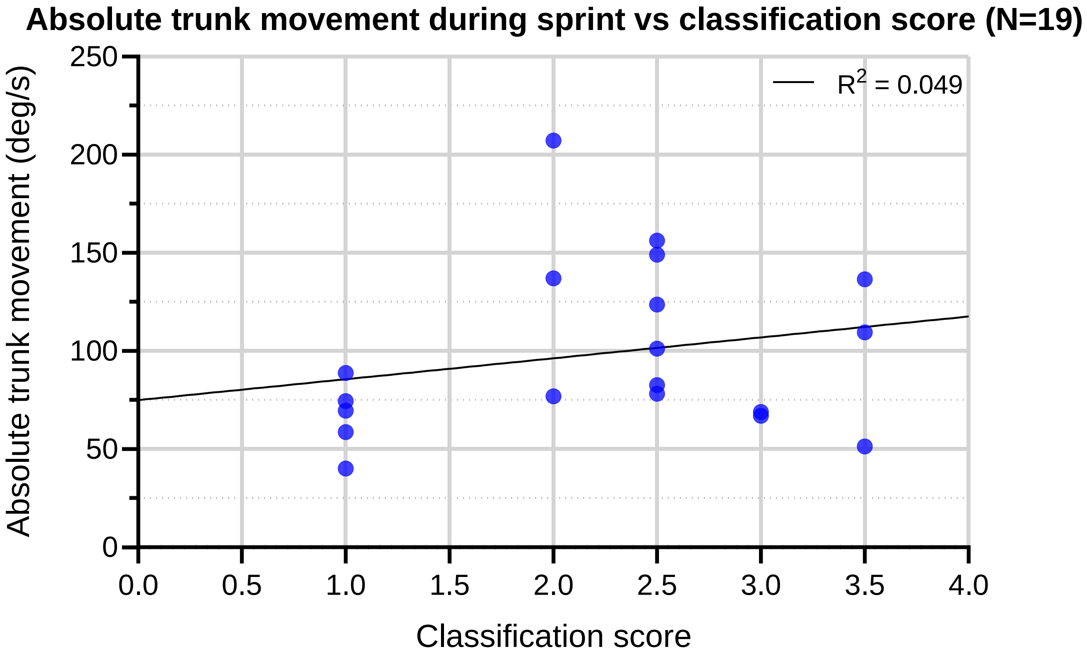


Figure 17: Scatterplot visualizing the relation between trunk movement during sprint and classification score

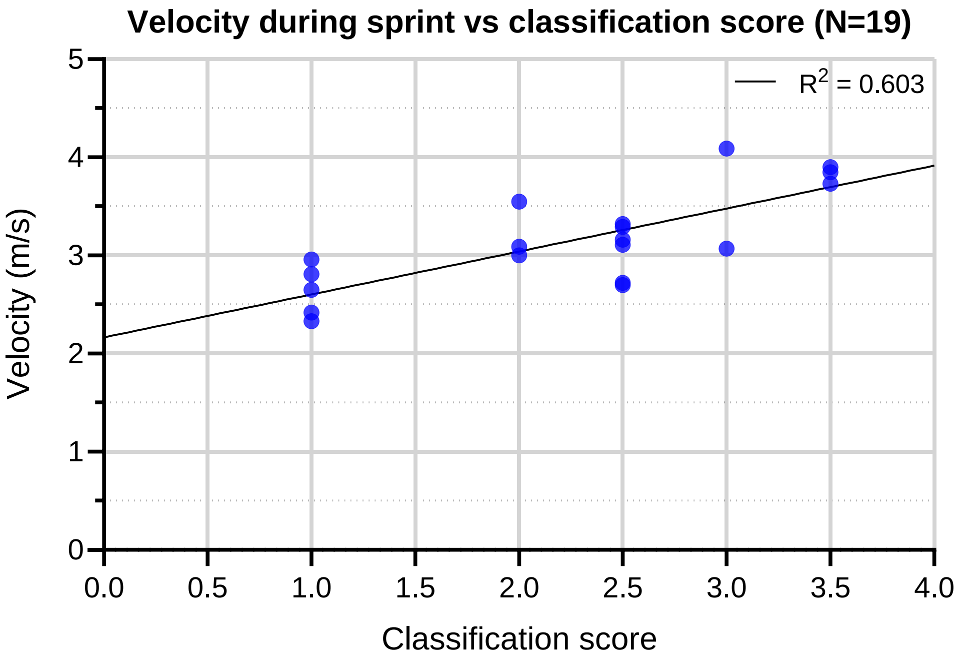
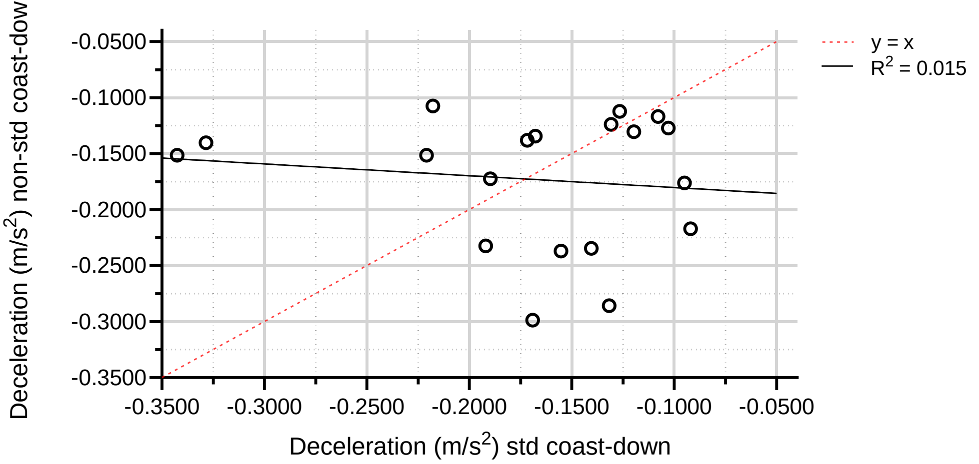


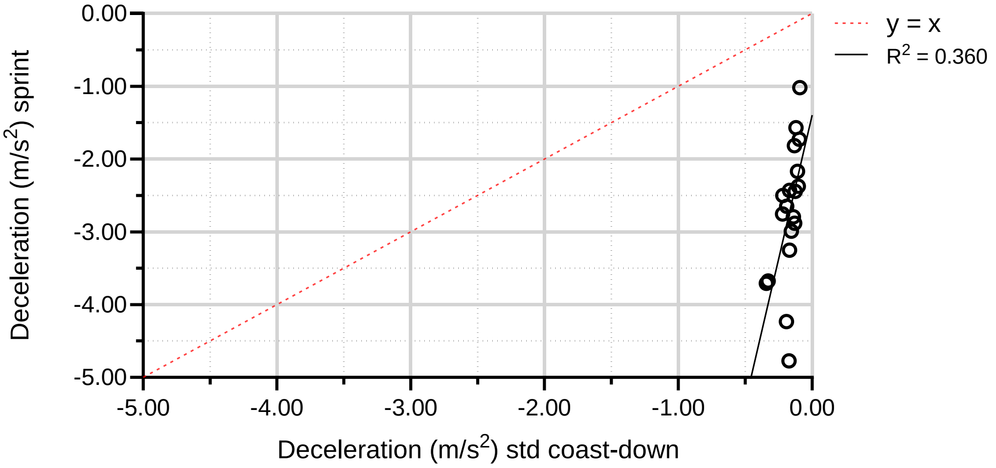
Figure 18: Scatterplot visualizing the relation between velocity during sprint and classification score

Appendix 4 Agreement between deceleration types

Deceleration non-standardized coast-down vs deceleration standardized coast-down (N=19)



Deceleration sprint vs deceleration standardized coast-down (N=19)



Deceleration sprint vs deceleration non-standardized coast-down (N=19)

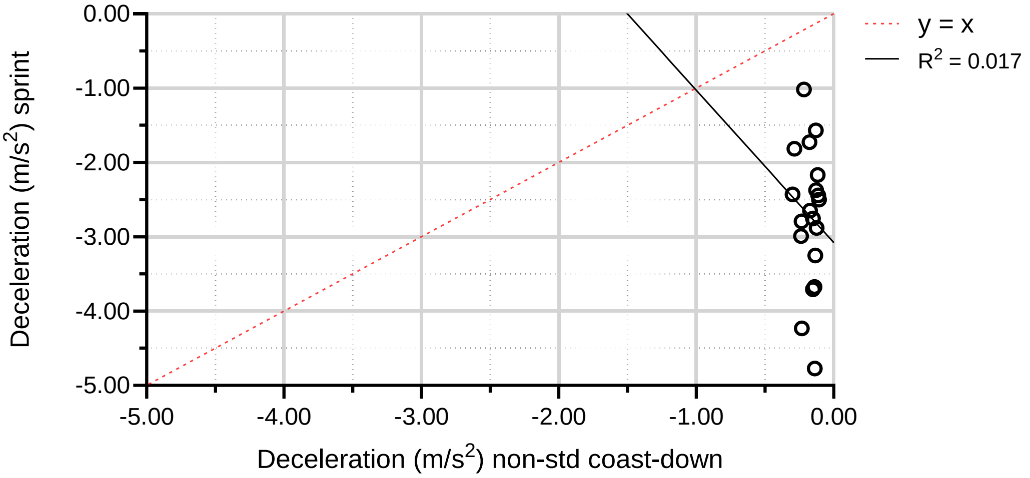


Figure 19: Scatterplots visualizing the agreements between deceleration types