Erwin van Huizen

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TU Delft

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By

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Abstract
This study investigates the key factors influencing the standing start in track cycling, aiming to identify the optimal technique for minimising starting time. High-speed video analysis and statistical methods were employed to analyse the standing starts of two cyclists, examining various movement and power variables to determine their correlation with the 15m split time. The gear ratio significantly impacted the 15m, 65m, and 125m split times.

Three hypotheses were tested. The first hypothesised that the more explosively a cyclist accelerates their body forward, as indicated by the maximum horizontal velocity of the hip and shoulder during the start, the faster the 15m split time. The results showed that the horizontal velocity of the hip did not significantly influence starting time. However, the horizontal velocity of the shoulder did have a significant impact, although the direction of the correlation differed between the two cyclists.

The second hypothesis proposed that better timing of hip acceleration would lead to a lower 15m split time. No significant results were found to support this hypothesis.

The third hypothesis stated that the optimal start movement would be associated with the highest power output during the first pedal stroke without resulting in slower split times. The normalised peak power output during the first pedal stroke demonstrated a strong, significant correlation with the 15m and 65m split times. Additionally, the maximum vertical hip velocity was significantly correlated with the 15m split time. Both vertical and horizontal hip velocity were correlated with normalised peak power, as was the angular velocity of the knee, partially supporting the third hypothesis.

These findings suggest that optimising the gear ratio and power production during the first pedal stroke is critical for a successful standing start in track cycling. Future research should investigate the optimal gear ratio by examining its effect on the 250m split time, as the ultimate goal for the starting rider is to complete the first lap as quickly as possible. Furthermore, the relationship between peak power production during the first pedal stroke and the 125m and 250m split times should be explored. If peak power production proves to be a reliable predictor, research should focus on identifying the movement that maximises peak power output during the first pedal stroke.

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1. Introduction

1.1. Background and relevance

Indoor racing on a wooden surface on a single speed bike with no brakes reaching speeds of over 80 km/h, also known as track cycling, has been around since 1893 (UCI, 2024). Since then, a lot of things have changed. The technology has made huge steps forward, due to the development of wind tunnels and ongoing research. Aerodynamic drag is the primary force to overcome in track cycling, which has led to significant improvements in helmets, suits, and bike design, the latter helping riders achieve a more aerodynamic posture. A recent change in bike geometry is the adoption of wide front forks, which sit in front of the rider's legs to "break" the air and improve airflow around the legs. Besides the air flow, the material choice for the bike has also changed a lot. The first bikes were made out of steel, but a search for lighter and stiffer materials led to the usage of titanium, magnesium, duralumin. Nowadays, carbon fibre is the main material used, due to the ability to tweak the stiffness of the frame in the desired places and directions.

There are two main categories in track cycling, being endurance and sprint events. The sprint events typically range between 250m and 1000m. The team sprint is one of the sprint events, with a length of 750 metres. A team of three riders start from a stand still and accelerate as fast as possible. The first rider swings off after one lap, the second rider swings off after the second lap and the third rider completes all three laps and that time is noted as the finish time. Since the year 2000 the team sprint is added to the Olympic cycling program for men and for women this is since 2012, although for women it changed from being a team of two to three as recently as in 2021.

The standing start is a type of start used in the team sprint in track cycling. Typically, a 10-second timer counts down, and when it reaches zero, the rider accelerates as quickly as possible from a stationary position. Most standing starts use a starting gate, see Figure 3, which clamps the frame or rear wheel of the bike, releasing the bike as the timer hits zero. In the team sprint only one rider starts from the starting gate, while the others are being held by a person. Riders are permitted to move before the timer hits zero, but the bike must remain stationary. The most popular technique nowadays involves pulling the body back and then thrusting the hips forward as the timer hits zero, thereby maximizing the amount of forward kinetic energy upon bike release.

At the latest World Championships in Ballerup, Denmark (2024), the time difference between first and fourth place was less than 1.3 seconds, illustrating that every detail can make the difference between winning a medal or going home empty-handed. Much research is done to describe and maximize performance and although the start is one of these extremely important moves in track cycling, as mentioned by Padulo et al. (Padulo, Laffaye, Bertucci, Chaouachi, & Viggiano, 2014), only Jansen and McPhee briefly describe the best starting technique in their paper (Jansen & McPhee, 2020). They describe four key stages of the standing start (Figure 1), being the pre-launch, gate release, drive and reset, but do not describe in detail what the best technique is, nor do they describe what the key factors are for a good start, except the timing of the forward motion of the cyclist. This leaves a gap in the knowledge of the best technique and key factors of the standing start.

Knowing the key factors can help coaches optimize start training for their athletes and ensure that they are focusing on the right things.

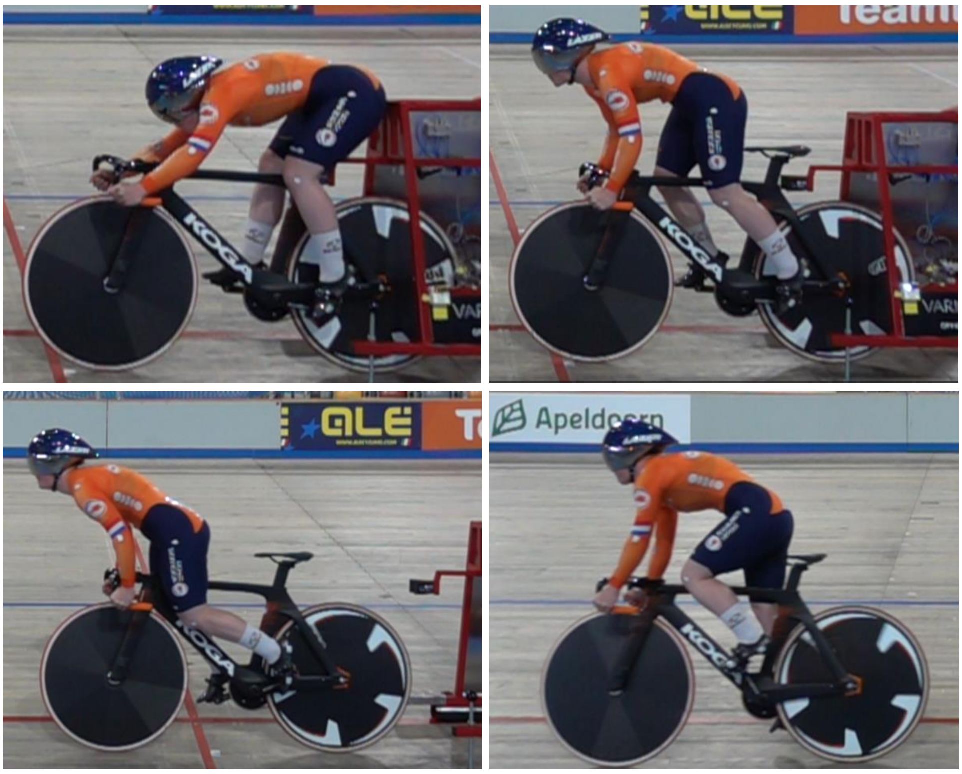


Figure 1 The four key stages in a standing start from Jansen and McPhee (2020). The stages from left to right are pre-launch, gate release, drive and the reset stage.

1.2. Research question and hypotheses

The main goal of the starting rider is to cover 250 meters in the shortest possible time. A recent study by Kordi and Van Rijswijk (2024) showed that a fast start is related to a fast initial lap. They used time data from 36 standing-start laps of 7 different elite sprint cyclists and found that the 15m split time has a strong, linear correlation with the 250m split time (r = 0,70). As the start is so important and the key factors are unknown, the aim of this research is to identify the key factors in the standing start. Consequently, the **research question** for this thesis is: *What are the key factors in the standing start in track cycling?* A key factor is defined as a variable that is significantly correlated to the starting time. These factors can be cyclists' body movements, power data, or environmental parameters. The primary focus of this research will be on cyclists' body movements, as this aspect has not been extensively studied before. The starting time is defined as the 15m split time. A general factor is defined as any variable which is not a movement variable, for example gear ratio, crank length, system's mass and air density are general factors.

Using the knowledge and experience of the coaches and riders, the following hypotheses have been formed. *The more explosively the cyclist accelerates their body forward, as seen in the maximum horizontal velocity of the hip and shoulder during the start, the faster the starting time, shown in the 15m split time (1).* The premise is that the cyclist weighs at least five times more than the bike and the cyclist's momentum generated by the thrusting movement of the hip will help accelerate the bike and cyclist faster when the bike is released. Some coaches tell the riders to focus not only on throwing the hip, but simultaneously throwing the shoulder forward as well. Because there is no unanimously ideal technique, both hypotheses will be tested. The second hypothesis is: *the better the timing of the acceleration of the hip, the lower the 15m split time (2).* The optimal timing is expected to be a combination of the maximum momentum and the position of the hip with respect to the pedals. The maximum momentum of the cyclist's body is linearly correlated with the maximum velocity of the cyclist's body as momentum is mass times velocity. The hip moves the most and is generally close to the centre of mass, making the maximum velocity of the hip most likely to be representative of the maximum momentum of the cyclist's body. The position of the hip with respect to the pedals is also expected to be relevant, as the cyclist cannot produce the same amount of power in every position or is not able to effectively put power to the pedals when, for example, leaning all the way back.

There are key factors that can potentially improve the 15m split time but may hinder performance over a longer distance. A well-known example is the gear ratio. A lower gear ratio enables the cyclist to accelerate more quickly, but as a cyclist can only pedal up to a certain cadence, it results in a lower top speed, making them slower over a full lap compared to using a higher ratio. Moreover, a high cadence leads to more fatigue (Wackwitz, Minahan, Menaspa, Crampton, & Bellinger, 2023). Therefore, an extra requirement is introduced: the key factor must not negatively impact the 65m or 125m split times. So, the third hypothesis is: *The optimal movement for the start is the one that is related to the highest power output during the first pedal stroke and is not related to slower split times (3).*

Figure 2 shows the starting positions of three different cyclists. There are some noticeable differences in body position. The cyclist on the right stands more upright compared to the two cyclists on the left. It is important to note that the cyclist on the right is significantly taller than the others and uses the opposite leg as the leading leg, making direct comparison of body positions challenging.

The optimal starting technique may vary depending on body type. To investigate this, the study examines two cyclists with contrasting body types, as shown by significant differences in height and mass (Table 1). First, the key factors for each cyclist will be identified individually by analysing multiple starts and assessing whether variations in movement result in changes in the 15m split time. Next, the key factors of both cyclists will be compared to determine whether the optimal starting technique and key factors are influenced by body type. If the key factors have a similar impact on starting time for both cyclists, it can be concluded that body type does not affect the optimal starting technique.

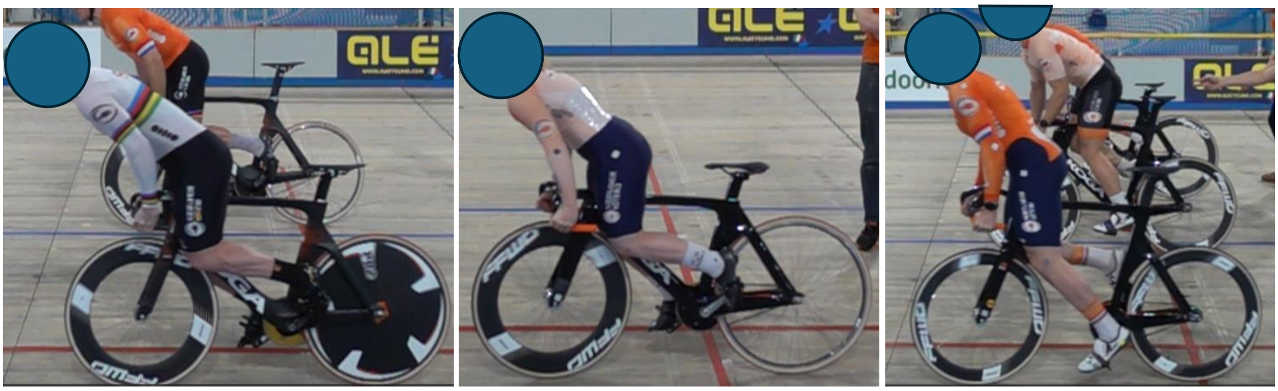


Figure 2 Different body positions for different cyclists.

2. Methods and materials

To study the correlation between the key movement factors and start time, video data of the first 10 meters of professional track cyclists' starts were collected and analysed. Additionally, split times and power data from these trials were recorded. A total of 48 starts by Cyclist A across 7 sessions and 29 starts by Cyclist B across 5 sessions were collected over 10 weeks.

2.1.1. Protocol data collection

The following data collection protocol was used to collect the data.

Riders

Two cyclists from the Dutch National Cycling Team (KNWU) participated in this study. Their details are shown in Table 1. The mass of the system was measured during each session, and small differences were observed between sessions. Table 1 presents the average mass and the deviation in mass for each rider across all sessions. Cyclist B switched halfway through the data collection period to a shorter crank with a length of 165 instead of 170mm.

Table 1 Details of the cyclists in this experiment.

	Age	Mass system* (kg)	Crank length (mm)
Cyclist A (female)	28	72,4 ± 0,9	170
Cyclist B (male)	21	103,0 ± 1,6	165/170
* Mass of the cyclist and bike combined			

Bike setup

Each rider used their own Koga Kinsei competition bike. The gear ratio varied per session and was recorded accordingly. The bikes were equipped with Dura Ace cranks and SRM X-Power PM9 pedals, which collected power data at a frequency of 200Hz. The pedals were calibrated before each session.

Velodrome

The data were collected at the Omnisport Velodrome in Apeldoorn, located 10 meters above sea level. The 250-meter track is made of Accoya wood.

Marker placement

Markers were placed on the riders and their bikes at the following points (indicated with grey circles in Figure 3):

- Shoulder (below the outer point of the acromion)
- Elbow (lateral epicondyle)
- Hand (metacarpophalangeal joint of the middle finger)
- Hip (greater trochanter)
- Knee (lateral end of the femur)
- Front of the shoe (indicating the toe)
- Back of the shoe (indicating the heel)
- Stem of the front fork (to track bike movement)

Reflective tape (30x30mm) was used for the bike, shoe, hip, knee, and helmet markers, while black markers were drawn on the suit for the elbow, ankle, and shoulder. The hand did not require a marker as the knuckle was trackable without one.

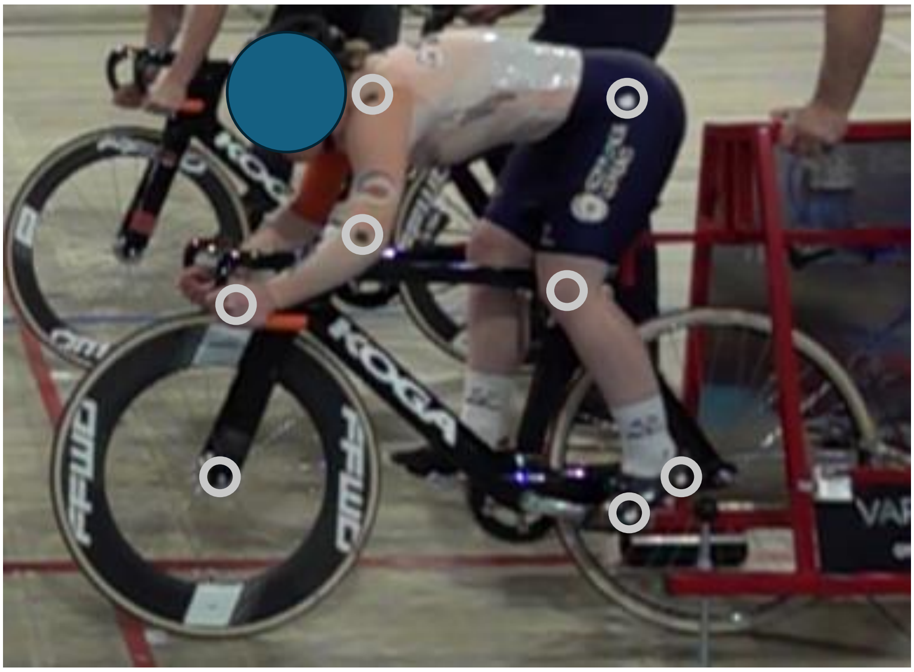


Figure 3 The locations of the markers used to track the movement of the cyclist.

Camera setup

A Sony RX100 V camera mounted on a fully extended tripod was used to film the start. The camera was positioned parallel to the track and aligned with the rider's motion, as shown in Figure 4.

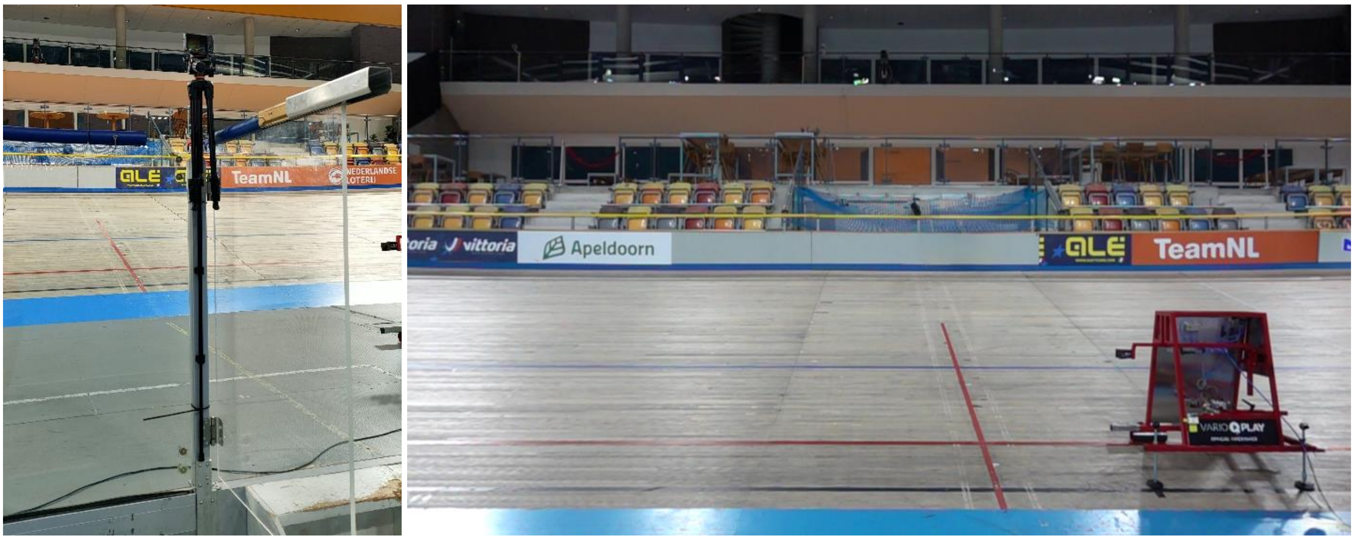


Figure 4 On the left is the setup of the camera with the tripod. The right image shows the field of view of the camera.

Camera settings

The camera was set to HFR mode, fully zoomed out, with a frame rate of 250 fps, creating a 5x slow-motion video at 50 fps. Shoot time priority is chosen as the priority setting and the recording starts when the trigger is pressed. Using these settings maximizes the recording time to around 7 seconds.

Arduino setup

An Arduino Nano with an accelerometer (ADXL345) was used to measure the opening of the gate (Figure 5). The code can be found in Appendix D – Code Arduino.

The box with an LED is mounted to the starting gate with some duct tape and it is made sure that the LED is visible for the camera (Figure 6). The accelerometer is connected to the piston, which keeps the wheel in place. The LED goes on for 3 seconds when the piston exceeds a threshold value of 7,5 m/s^2.

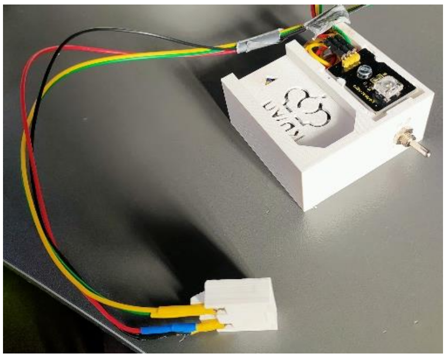


Figure 5 Device used to measure the timing, including an Arduino and an accelerometer.

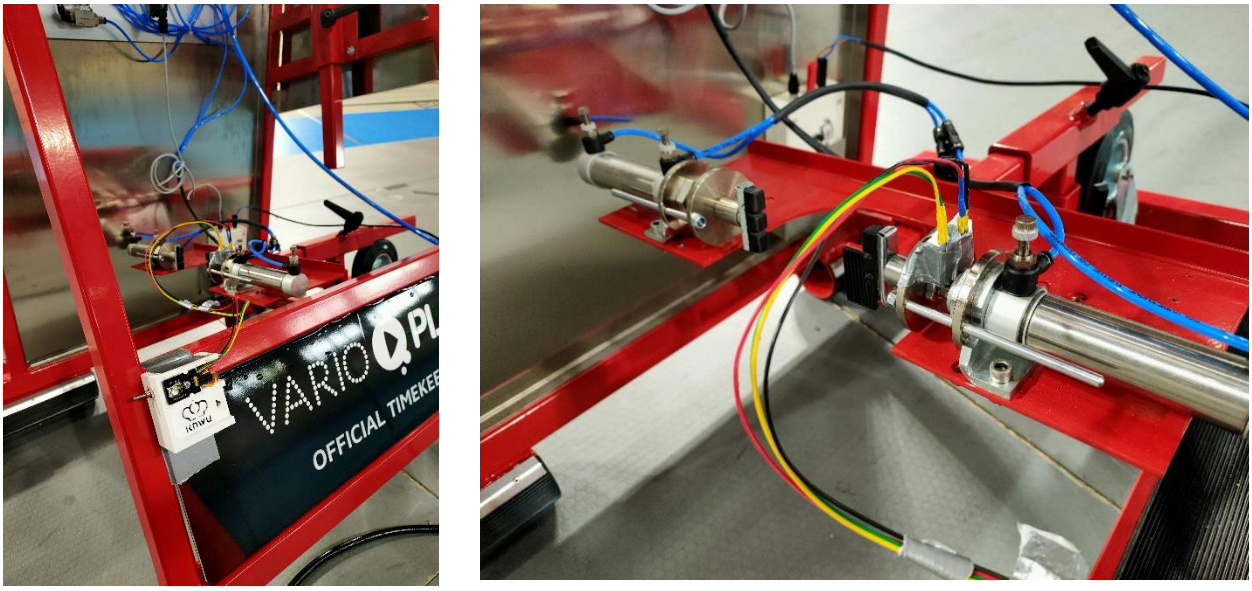


Figure 6 The Arduino and accelerometer mounted to the starting gate.

2.1.2. Measuring data

Separate folders were created to store the data for each of the riders. The printed form, 'data_gathering_form' (Appendix A – Form data collection), is used to collect all the data during the trials, except from the power, time and video data, which are stored electronically. The forms were also digitised after the training.

Before training

Before training, the plan for the number of starts and gear ratios was gathered from the coach. Environmental data (air density, air pressure, humidity, and temperature) were collected before and after each session using a Kestrel 5100 racing weather meter.

During training

Power output and cadence were recorded at 200Hz using SRM pedals. Start and split times were captured using the MYLAPS ProChip system for distances of 15m, 65m, 125m, 150m, and 250m. The camera captured the first 10 meters of each start. After each start the rider blindly rated the performance on a scale of 1 to 10 and the reason for the rating.

After training

After each training the power data were retrieved from the crank and together with the video data and time data stored in a folder named: 'training_date_Cyclist_A/B' on a personal computer and a back-up of the data was stored on a personal external hard drive. The printed form was digitalized and stored in the same folder. The videos were named c00[number of the video].mp4 and the power data were stored with the same number.

2.2. Data processing

After data collection, video and power data were processed. Kinovea was used to track marker locations during the start. Kinovea (version 0.9.5, www.kinovea.org) is a free and open-source video annotation tool, specially designed for analysing sport. The joint position data were saved in .csv files and analysed using MATLAB R2021B, where it was filtered and plotted.

2.2.1. Kinovea

Tracking the markers in Kinovea was done as follows:

- The video is loaded into Kinovea.
- Where the wheels touch the track, a line between the two seams in the track is drawn and used to define the length of a pixel in the video, Figure 7. The line is 314cm long in real life.

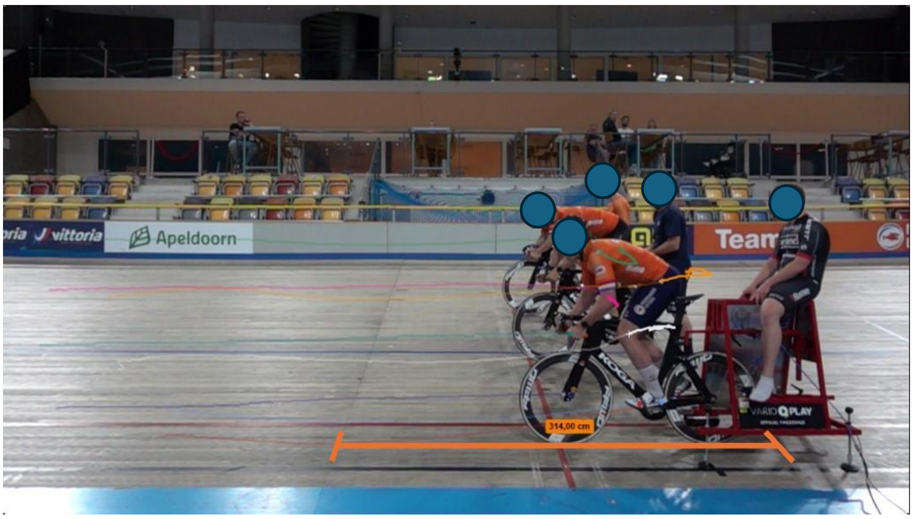


Figure 7 Definition of the line used to go from pixels to meters in Kinovea.

- Using tools>Coordinate system it is checked to see if the origin lies at the seam below the starting machine and if the axes are aligned horizontally with the line of motion, Figure 8.
- When the LED light goes on, the time is set to 0.

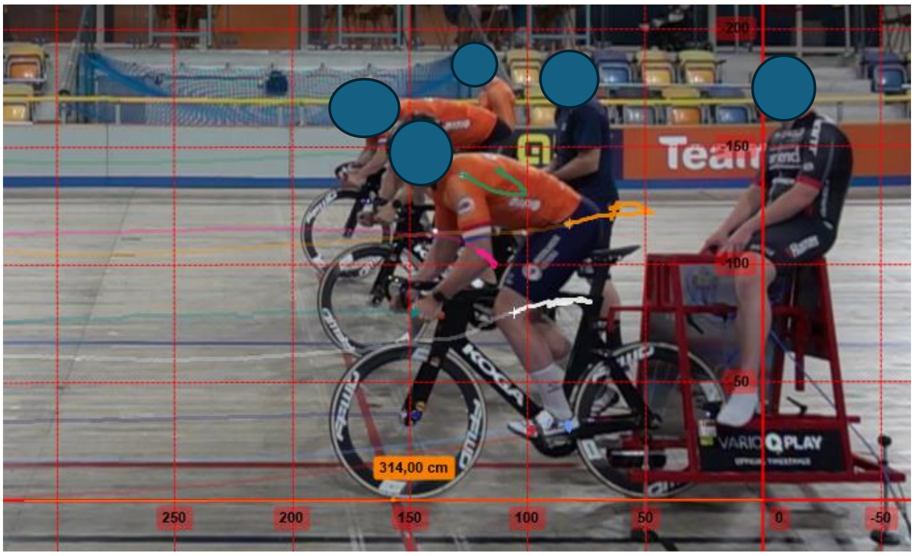


Figure 8 Correct setup of the coordinate system in Kinovea.

- The video is stopped when the bike starts moving and the time between the LED going on and the movement of the bike is written down as the timing. The time is again set to 0 in order to rule out the differences in timing and only keep the differences in movement.
- Markers are added to the markers visible in the video. This is done by right clicking and selecting ‘Track path’. After right clicking on the area around the marker and selecting ‘configuration’, a window pops up. Here the marker is named after the joint that it tracks. A marker is added to the front fork, hip, shoulder, elbow, hand, knee, ankle and toe. The object window is set to 25 by 25 pixels, and the Search window is set to 100 by 100 pixels. These values are determined by running multiple tests with multiple values and it turned out that these values gave the smoothest results.
- After playing the full video, all the markers are tracked.
- The data are exported by clicking tools>Linear kinematics. Here the horizontal position and vertical position are separately exported by clicking ‘Save to file’ in the ‘Export data’ box. The data are stored in a .csv file. The horizontal data are stored as c00[number of the video]xposition.csv and the vertical data are stored as c00[number of the video]yposition.csv.
    - In my case the time origin in the .csv file did not correspond to the time origin in the video, so this was corrected manually in the .csv file.
- An extra column is added to the .csv file for the location of the saddle. This is done by subtracting the location of the saddle from the marker of the front fork. For cyclist A the distances are x = -75cm and y = +52cm and for cyclist B this is x = -81cm and y = +67cm.
- Finally, the annotations to the video file are saved separately.
- Note that Kinovea standardly filters the data using a Butterworth filter, but this option was disabled for this project.

Matlab

All the x- and y position data were loaded into MATLAB and filtered using a 6th order Butterworth filter with a cutoff frequency of 2Hz and a sampling rate, which is similar to the frame rate of the video, of 50Hz. Because of the effect of the filtering the last 10 samples of the x- and y data are disregarded after filtering. After filtering the position data were differentiated twice to obtain the velocity and the acceleration of the joints. The position, velocity and acceleration of the joints were plotted from when the rider stands up until the front wheel disappears from the video, which is from around -4 till + 1,5 seconds. There is also a variation of this script which also filters the data, but then calculates the joint angles, angular velocities and angular accelerations and plots them in time. The code can be found in Appendix E – Code data processing Matlab.

2.3. Modelling changing air density and mass

The data were gathered on different days, which led to differences in the air density. The mass of the entire system (cyclist and bike) also varied between the sessions. To correct the split times for these changes, a simplified model was developed to estimate the additional time that changes in mass and air density would contribute to the different split times. The model is based on the power needed to overcome drag forces, as shown in Eq. 1. To simplify the model, friction in the system (e.g., drivetrain efficiency) and changes in gravitational energy are neglected, focusing only on rolling resistance and air resistance.

$$P_{drag} = C_{rr} m g v + \frac{1}{2} \rho C_d A v^3 \tag{1}$$

P_{drag}	= power needed to overcome drag (W)
C_{rr}	= rolling resistance coefficient
m	= mass of the system (kg)
g	= gravitational acceleration (m/s^2)
v	= velocity of the system (m/s^2)
ρ	= air density (kg/m^3)
C_d	= drag coefficient
A	= frontal area of the system (m^2)

The working principle of the model is as follows: a known velocity profile from an experiment is used to calculate the power required to overcome drag. By altering the mass and air density, a new velocity profile is generated, assuming the power required to overcome drag remains constant for each step. Using the new velocity profile, the time it takes for the cyclist to reach 15m, 65m, and 125m is calculated. The time difference between the split times of the old and new velocity profiles is defined as the additional time.

The primary assumption for this model is that the power required to overcome drag remains constant. This assumption is justified because the standing start is an all-out sprinting performance where the cyclist aims to maximise power output. The velocity profile is calculated using Eq. 2.

$$v(t) = \omega_{crank}(t) * r_{wheel} * G_{ratio}$$

2

$v(t)$	= velocity profile in time (m/s)
$\omega_{crank}(t)$	= angular velocity of the crank in time (rad/s)
r_{wheel}	= radius of the back wheel (m)
G_{ratio}	= gear ratio

The angular velocity captured by the crank is used to calculate the horizontal velocity of the bike at each time point. The angular velocity of the crank is linked to the angular velocity of the rear wheel via the gear ratio, which is defined as the number of teeth on the front chainring divided by the number of teeth on the sprocket. Multiplying the number of wheel rotations by the radius of the rear wheel gives the distance travelled by the bike. The circumference of the wheel was measured to be 2,095m. The radius is therefore $2.095/2\pi$, approximately 0,334m. Figure 9 displays the original velocity profile (black) alongside several newly calculated velocity profiles based on varying mass and air density. The bottom graph provides a close-up view of the top graph. The figure reveals that changes in mass have minimal impact on velocity, while changes in air density have a significant effect. An increase in air density results in a decrease in velocity, whereas a decrease in air density leads to an increase in velocity. The code for the model is included in Appendix B.

The drag coefficients and frontal area were unknown for this study. Blocken et al. analysed the 'CdA' for different sprinting positions on the bike (Blocken, van Druenen, Toparlar, & Andrianne, 2019). They found that in a regular sprinting position - standing on the pedals with the head near the bars - the frontal area was 0,46 m^2 and the drag coefficient was 0,67 when the wind speed was 15m/s. During the standing start, the cyclist begins upright on the pedals and generally sits near 65m, resulting in continuous changes in the frontal area and drag coefficient. Given the difficulty of measuring these variables for all time points, estimates were made based on the study by Blocken et al. At the start, the cyclist's position is more upright than in the study, leading to higher frontal area and drag coefficients. The frontal area was set to 0,5m^2, and the drag coefficient to 0,9. The rolling resistance coefficient was also unknown for this study. Using Underwood's study, the rolling resistance coefficient was set to 0,0018 (Underwood, 2012).

The velocity profile was unavailable for approximately half of the trials due to the absence of crank data. When the velocity profile for a specific trial was unavailable, a profile from a trial with the same or closest gear ratio was used to calculate the additional time. If multiple profiles with the same gear ratio were available, all were tested, and the average additional time was calculated.

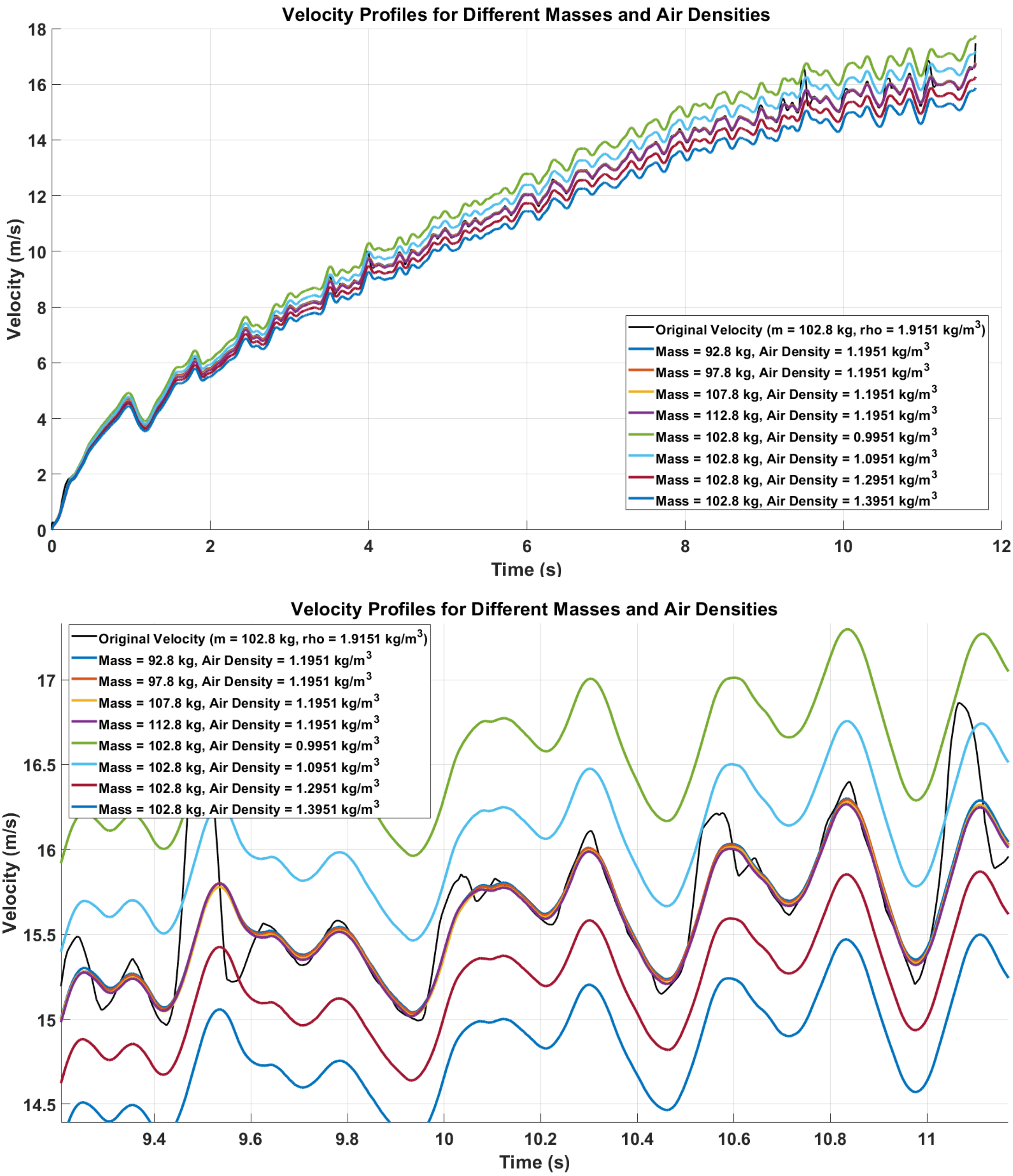


Figure 9 The top figure shows the original velocity profile and the new velocity profiles for changes in mass and air density. The bottom figure shows a close-up of the velocity profiles in the top figure.

2.4. Statistical analysis

Pearson's correlation coefficients were calculated separately for each cyclist in Excel using the regression function from the Data Analysis ToolPak to identify linear correlations between the split times and movement or other potentially important variables. This function returns the correlation coefficient (r) and significance (p). A correlation is considered moderate when $|r| = 0{,}3\text{-}0{,}5$ and strong when $|r| > 0{,}5$. A significance of $p < 0{,}05$ is considered to be statistically significant. Second-order polynomial correlations were tested where non-linear relationships were expected. The split times were corrected for differences in timing and position of the starting machine, as well as for changes in mass and air density between the sessions.

Before calculating the correlation between the split times and the movement variables, a two-tailed t-test was used to test whether the different crank lengths had a significant impact on the corrected 15m, 65m, and 125m split times. To test significance of the impact of the gear ratio on the split times, linear correlation was used. Although this study focuses on the 15m split time, it is important to examine the impact on all the split times for general factors, as a key factor must not negatively affect the 65m and 125m split times. The gear ratio was found to have a significant impact on the split times for Cyclist A. Therefore, to identify key movement factors, a multiple regression analysis was performed, using the gear ratio and a movement variable as independent variables. Cyclist B used two crank sets of different lengths. The crank length was found to have a significant impact on the 15m split time based on the t-test results. Consequently, a multiple regression analysis with the crank length and a movement variable as independent variables was conducted to identify key movement factors. Within the multiple regression analysis, the crank length was never statistically significant. To ensure that key movement factors were identified without neglecting the influence of crank length, two datasets were created (one for each crank length) and used to calculate the correlations between the movement variables and the 15m split time.

Finally, the correlations between the power data and the 15m split time were calculated. When a power variable significantly predicted the 15m time, the correlation between this power variable and the movement data was also calculated. This approach could provide valuable insights into how power production is coupled with the rider's movement.

2.5. Definition of tested variables

2.5.1. General variables

Split time

Split time (in seconds) is defined as the time from the opening of the gate until the rider passes a specific split line. There are split lines at 15, 65, 125, 150, and 250 meters, the last representing one full lap around the track. The split time is recorded using MyLaps technology with a chip placed in the front fork of the rider's bike. Timing begins when MyLaps receives a signal from the starting gate and stops when the bike passes the loop under the split line. This study primarily focuses on the 15m split time; however, if additional split times are available, they will be considered to ensure that any identified predictors do not negatively affect performance over longer distances.

Distance to starting line

The starting machine is moved regularly, causing slight variations in its position. The distance to the starting line (in centimeters) is defined as the distance between the centre of the wheel and the front side of the red line (Figure 10).

Cyclist A typically rides at an average speed of 7.5 m/s, and Cyclist B at approximately 8 m/s when passing the 15-meter line. The differences in starting position are corrected by subtracting the time it takes to travel the additional centimeters at a constant velocity using Eq. 3.

$$t_{additional} = \frac{x_{red}}{v_{15m}}, \qquad where \tag{3}$$

$t_{additional}$ = additional time due to different starting positions of the gate (s)
x_{red} = distance between the center of the front wheel and the front of the red line (m)
v_{15m} = average velocity of the cyclist after 15 meter (m/s)

Figure 10 Definition of the distance to the red line. Measured from the centre where the wheel touches the floor and the furthest point of the red line.

By subtracting the additional time from the MyLaps time, the corrected time represents the time it takes for the transponder in the front fork to travel from the red line till the 15, 65 and 125-meter line.

Timing

Timing (in seconds) is defined as the time between the opening of the gate and the first movement of the bike. In this study, it was not possible to synchronize torque data with MyLaps' starting time in real-time. Therefore, the only indication of timing is the first movement of the bike, which cannot occur before the gate is released, meaning negative timing is impossible. The opening of the gate is indicated by a white LED, and timing is recorded using video data.

Gear ratio

For each start, the size of the chainrings and the sprocket is noted. The gear ratio is defined as the size of the front chainring divided by the size of the rear sprocket, yielding a value typically between 3 and 4.5.

2.5.2. Movement variables:

To find correlations between the times and the movement of the rider, the variables shown in Table 2 were tested. When a specific joint is mentioned, the corresponding marker to that joint is used to find the value of the variable. The movement variables are all about the launch phase, which consists of the movement just before the gate opens and the first 10 meters of the start. Only this part is captured by the camera.

Table 2 Definition of the different movement variables tested.

Maximum Horizontal Velocity of the Joints (m/s)	The maximum horizontal velocity is the peak velocity of a specific joint during the launch phase, relative to the bike's velocity. The movement of the joint is isolated by subtracting the bike's velocity. The horizontal velocity is tested for the hip, shoulder, elbow, and knee, as only horizontal acceleration contributes to the bike's forward motion.
Time Above 70% and 90% of Maximum Hip Velocity (s)	This variable represents the time above 70% and 90% of peak horizontal hip velocity during the launch phase. It indicates the duration of the launch motion.
Distance Hip Pulled Back (cm)	This variable defines the distance that the hip moves backward relative to the saddle during the launch phase.
Most Forward Hip Position (cm)	The most forward hip position is the farthest forward the hip moves during the first pedal stroke, relative to the saddle. This variable helps describe the hip's motion.
Timing of Hip and Gate Opening (s)	This variable is the time between the maximum horizontal hip velocity during the launch phase and the gate opening. It provides insight into how well the rider times their body motion with the gate release.
Vertical Hip Velocity (m/s)	Vertical hip velocity refers to the maximum vertical speed of the hip during the first pedal stroke, when the body ‘resets’ to push down on the opposite pedal. It may indicate how effectively the pedal strokes are connected and how quickly the cyclist transitions to an efficient, power-generating position.
Maximum Angular Velocity of the Joints (deg/s)	This variable measures the maximum or minimum angular velocity of a joint during the launch phase and first pedal stroke. Maximum and minimum values are recorded for the hip, elbow, and shoulder, while only negative angular velocities are measured for the knee and ankle.

2.5.3. Power variables

The moment of the start is identified using the crank angle, not the crank torque. In Figure 11, it can be observed that the crank torque is above zero, while the crank angle remains constant. The rider applies force by standing on the pedals, generating some torque due to gravity and preparatory motion. The crank angle decreases slightly before increasing rapidly. The moment the crank angle begins to rise is defined as the start (t = 0). Table 3 shows the different power variables that were tested and their definitions.

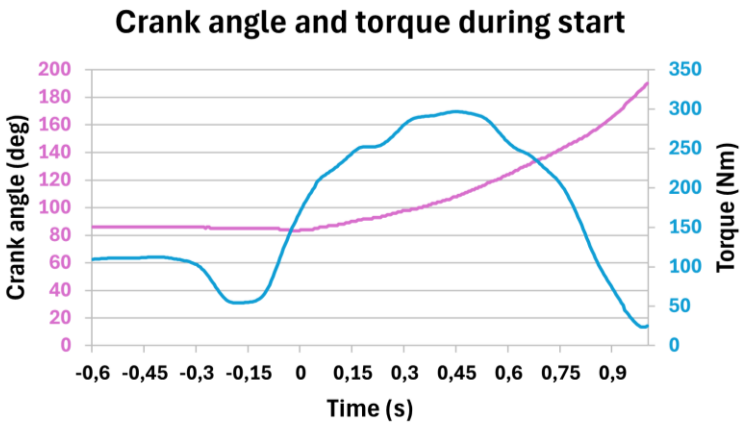


Figure 11 An example of the crank angle and the crank torque, used to define the moment of the start.

Table 3 Definition of the power variables tested.

Maximum Torque Peak during First Pedal Stroke (Nm)	This variable measures the maximum torque exerted during the first pedal stroke. The first pedal stroke is also captured on video, allowing for potential correlation between the motion and the torque peak.
Normalised Peak Torque (W/kg)	This variable is the peak torque divided by the combined mass of the cyclist and bike. It accounts for changes in system weight between different sessions.
Time Above 70% and 90% of Maximum Torque Peak (s)	A variation of the maximum torque peak is the time the rider spends above 70% and 90% of the peak torque during the first pedal stroke.
Crank Angle Range Over 70% and 90% of Maximum Torque (degrees)	Bertucci et al. (2008) propose another variation—the crank angle range over which the rider produces 70% or 90% of the maximum torque peak during the first pedal stroke. This is calculated using the torque data and crank angle.
Time to Maximum Torque Peak (s)	Time to maximum torque peak is the time from t = 0 to the maximum torque peak during the first pedal stroke.
Maximum Power Peak (W)	The maximum power peak is the first power peak during the first pedal stroke. Since power is a product of torque and cadence, this variable provides insights into both torque and cadence.
Normalised Peak Power (W/kg)	This variable is the maximum power peak divided by the mass of the cyclist and bike, accounting for changes in weight across different trials.
Time to Peak Power (s)	This variable refers to the time taken to reach the first power peak. The power peak does not necessarily coincide with the torque peak, so this variable offers insights into when maximum velocity is achieved.

3. Results

Movement data and split times were recorded for 48 starts across 7 days for Cyclist A, and for 29 starts across 5 days for Cyclist B. Power data were available for 20 starts for Cyclist A and 13 starts for Cyclist B, as some data were not correctly stored on the crank system. Before examining the correlation between the 15m split time and the movement variables, the relationship between the general factors and the split times was analysed to determine whether adjustments to the split times were necessary due to changes in these factors between sessions.

Environmental variables were measured before and after each training session, with the average of the two measurements used as the mean value for that day. Table 4 summarises the average environmental conditions. On days when air density measurements were unavailable (n = 3), air density was calculated using other recorded parameters, as described in Appendix C. Using the model from Section 2.3, the split times were compensated for changes in mass and air density between the different days.

Table 4 Environmental variables recorded during data collection. Mean and standard deviation are shown.

	Air Pressure (hPa)	Temperature (°C)	Humidity (%)	Air Density (kg/m^3)
Cyclist A	1014,3 ± 5,8	22,1 ± 1,7	51,1 ± 6,3	1,191 ± 0,008
Cyclist B	1014,0 ± 5,1	23,1 ± 1,5	55,1 ± 3,2	1,185 ± 0,006

Gear ratio

Figure 12 and Figure 13 show the correlation between gear ratio and split times. The average split time per gear ratio is plotted, with error bars representing the standard deviation. Where no error bars are shown, the standard deviation was 0 because there was only one measurement in that category.

For Cyclist A, a strong, significant correlation was observed, particularly for the 65m and 125m split times, with correlation coefficients around 0,9 and p-values much smaller than 0,05. For the 15m split time, the gear ratio explained less of the variation but still accounted for 55%, indicating the influence of additional factors. For Cyclist B, no significant correlation was observed between gear ratio and split times. Consequently, only for Cyclist A will the gear ratio be taken into account for the 15m split time, as it is statistically significant.

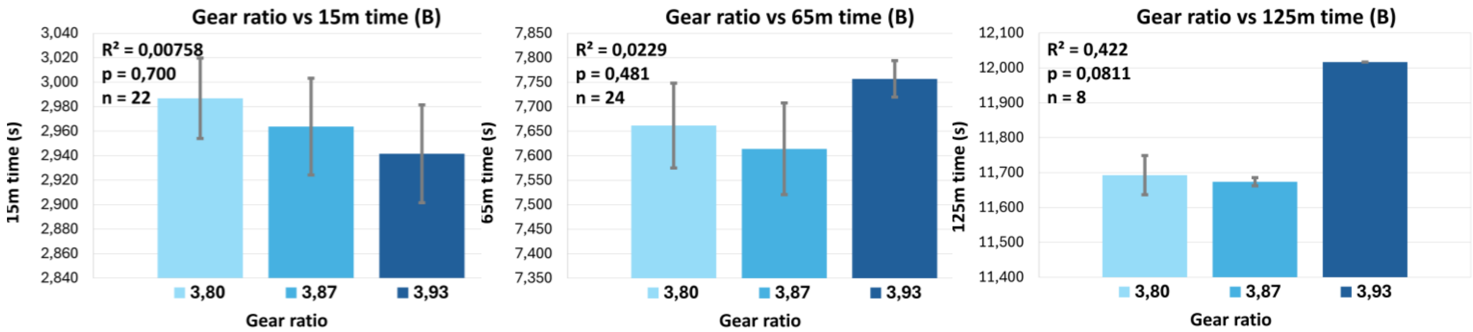


Figure 12 Average split time versus the gear ratio. The error bars show the standard deviation.

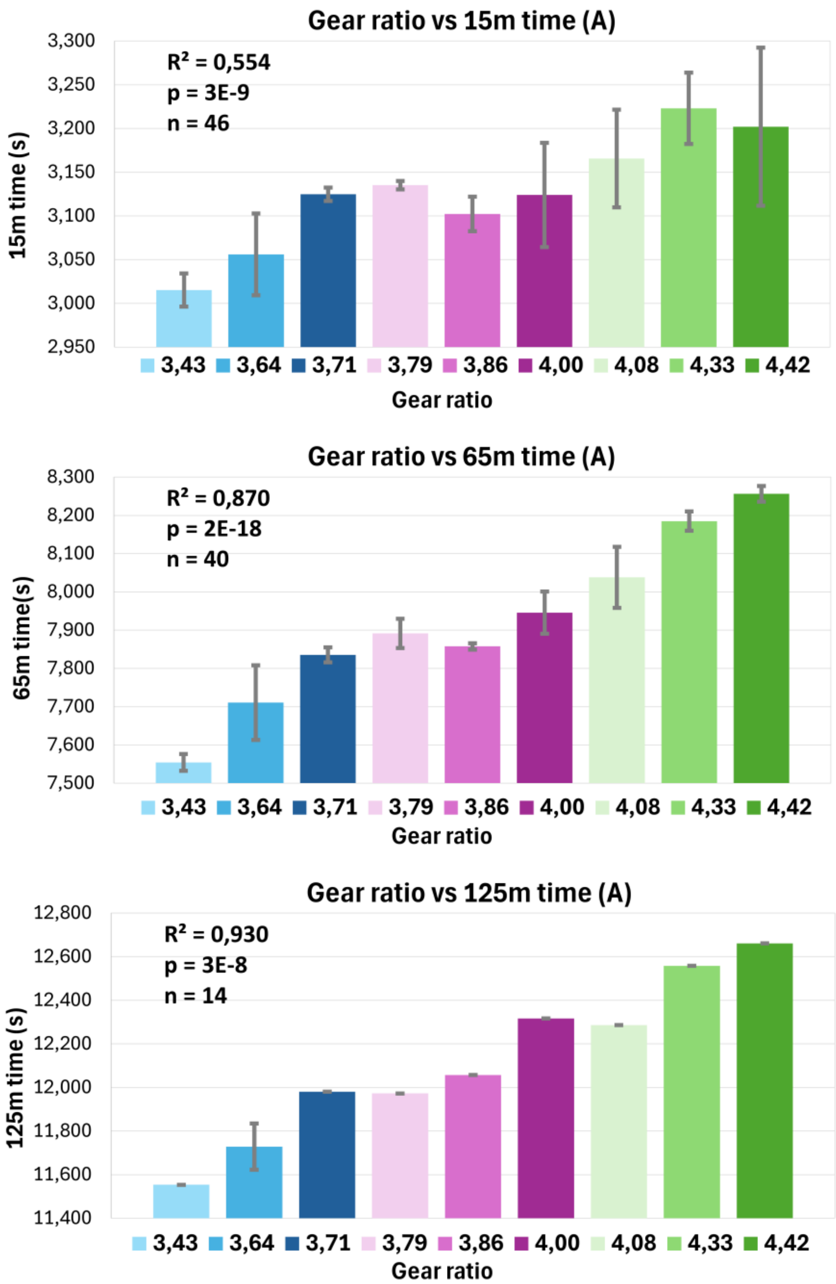


Figure 13 Gear ratio versus average split time for cyclist A. The error bars represent the standard deviation.

Crank length

Table 5 presents the mean and standard deviation of the split times for each crank length, besides the amount of split times for each crank length (n). Also the t-test results (significance (p) and t-statistic) and the linear correlation coefficient between the crank length and split times are in the table. As only Cyclist B used two different crank lengths, only the results for Cyclist B are shown. Crank length showed a significant correlation for the 15m and 65m split times and will, therefore, be considered in the analysis of the 15m split time.

Table 5 Mean and standard deviation of the split times for each crank length. The results of the t-test and the linear correlation coefficient are also shown.

		170mm crank		**165mm crank**		**t-test results**		**correlation**
		Mean ± S.D.	n	Mean ± S.D.	n	p	t-stat	r
Cyclist B	15m time (s)	2,968 ± 0,032	9	3,009 ± 0,037	13	**0,0162**	**2,63**	**-0,506**
	65m time (s)	7,600 ± 0,049	12	7,691 ± 0,113	12	**0,0270**	**2,45**	**-0,463**
	125m time (s)	11,688 ± 0,177	2	11,840 ± 0,047	6	0,553	0,847	-0,558

3.1. Movement variables

The primary goal of this study was to identify key movement variables during the standing start. Table 6 presents the results of all the movement variables for both the cyclists. For cyclist A, no angular velocity for the knee was collected as the marker on the ankle was not visible for the first two days and the marker on the knee was hard to track. The number of data points

In general, there is a lot of variation in almost all the movement variables, which is good to find the impact of the movement variable on the split time, if the split times themselves also vary.

Table 6 Variation in movement variables, with the mean, standard deviation and range of each movement variable.

	Cyclist B		**Cyclist A**	
	Mean ± S.D.	Range	Mean ± S.D.	Range
Angular velocity hip (deg/s)	321 ± 33	120	242 ± 17	68,2
Angular velocity shoulder (deg/s)	-302 ± 13	46,0	-238 ± 24	103
Angular velocity shoulder (deg/s)	202 ± 21	90,6	312 ± 29	151
Angular velocity knee (deg/s)	-229 ± 27	109		
Angular velocity ankle (deg/s)	-229 ± 29	113	-173 ± 35	170
Angular velocity elbow (deg/s)	-209 ± 31	152	-221 ± 39	172
Angular velocity elbow (deg/s)	150 ± 46	209	157 ± 24	104
Horizontal velocity hip (m/s)	2,54 ± 0,15	0,597	1,90 ± 0,10	0,480
Hip velocity first stroke (m/s)	-1,52 ± 0,22	0,980	-2,02 ± 0,18	0,700
Time above 70% hip velocity (s)	0,176 ± 0,017	0,0680	0,148 ± 0,024	0,124
Time above 90% hip velocity (s)	0,0800 ± 0,0182	0,0680	0,0788 ± 0,0191	0,0880

	Mean ± S.D.	Range	Mean ± S.D.	Range
Time between maximum hip velocity and opening of the gate (s)	0,00890 ± 0,0209	0,0840	-0,00825 ± 0,0159	0,0760
Distance hip pulled back (cm)	-18,7 ± 2,1	8,90	-17,0 ± 2,0	8,30
Position hip at opening of the gate (cm)	19,3 ± 5,2	18,7	10,6 ± 3,63	16,5
Most forward position hip (cm)	64,3 ± 1,5	6,40	54,9 ± 1,4	7,00
Horizontal velocity shoulder (m/s)	1,43 ± 0,08	0,340	1,44 ± 0,11	0,480
Horizontal velocity elbow (m/s)	1,01 ± 0,13	0,680	0,986 ± 0,099	0,529
Horizontal velocity knee (m/s)	2,27 ± 0,14	0,570	1,05 ± 0,14	0,600
Vertical velocity hip (m/s)	0,675 ± 0,10	0,389	1,09 ± 0,092	0,336

3.1.1. Movement variables versus starting time

The results of the correlation between the movement variables and the 15m split time for cyclist A, are shown in Table 7, and for cyclist B in Table 8. The 15m split times were corrected for differences in timing, the position of the starting machine, and changes in mass and air density between sessions. For movement variables that significantly correlate with the 15m split time, the correlation with the 65m and 125m split times is also shown at the bottom of the table.

Cyclist A

For cyclist A, a multiple regression analysis, where the gear ratio is combined with a movement variable was used to predict the 15m split time. All movement variables tested, produced an overall significant result in the multiple regression analysis, due to the gear ratio itself having a significance of 3,00E-09. Therefore, $P_{movement}$ was added to the table, which represents the significance of the movement variable in the prediction. The average value of each movement variable and the number of data points were also added. Finally, the coefficient for each movement variable was included to indicate its influence on the 15m split time. A negative coefficient leads to a faster 15m split time unless the movement variable itself is negative.

Table 7 Correlation between the movement variables and the 15m split time. The significance is indicated by the p-value.

	Cyclist A			
	$P_{movement}$	$\bar{x}_{movement}$	Coefficient movement	n
Angular velocity hip (deg/s)	0,132	242	0,000717	45
Negative angular velocity hip (deg/s)	0,166	-340	-0,000358	45
Negative angular velocity shoulder (deg/s)	0,0888	-238	-0,000549	45
Angular velocity shoulder (deg/s)	0,637	312	0,000128	45
Angular velocity ankle (deg/s)	0,0757	-173	-0,000471	36
Negative angular velocity elbow (deg/s)	0,105	-221	-0,000319	45
Angular velocity elbow (deg/s)	0,481	157	-0,000237	46
Horizontal velocity hip (m/s)	0,491	1,90	0,0506	46

		$P_{movement}$	$\bar{x}_{movement}$	*Coefficient movement*	*n*
Negative hip velocity first stroke (m/s)		0,372	-2,02	-0,0370	46
Time above 70% hip velocity (s)		0,823	0,148	0,0746	45
Time above 90% hip velocity (s)		0,925	0,0788	-0,0387	45
Time between peak hip velocity and gate opening (s) – linear		0,205	-0,00825	0,617	46
Time between peak hip velocity and gate opening (s) – 2nd ord. polynomial	X:	0,395	-0,00825	0,724	46
	X^2:	0,109		49,8	
Distance hip pulled back (cm)		0,618	-17,0	-0,00188	44
Position hip at opening of the gate (cm)		**0,0224**	**10,6**	**-0,00500**	**46**
Most forward position hip (cm)		0,208	54,9	-0,00750	46
Horizontal velocity shoulder (m/s)		0,0511	1,44	-0,139	45
Horizontal velocity elbow (m/s)		0,997	0,986	0,000307	45
Horizontal velocity knee (m/s)		0,0615	1,05	-0,101	45
Vertical velocity hip (m/s)		0,637	1,09	0,0433	45
Maximum horizontal velocity shoulder and hip (m/s)	S:	0,0404	-	-0,147	45
	H:	0,255	-	0,0817	
Position hip at opening of the gate (cm)	65m	0,292	11,2	-0,00404	40
Position hip at opening of the gate (cm)	125m	0,315	11,5	-0,00828	14

Only the position of the hip relative to the saddle at the opening of the gate is statistically significant (see Figure 14). A higher vertical velocity results in a faster 15m split time. The maximum horizontal velocities of the shoulder and knee are close to statistical significance. When combining the maximum velocities of the hip and shoulder to predict the 15m time, the horizontal velocity of the shoulder becomes statistically significant.

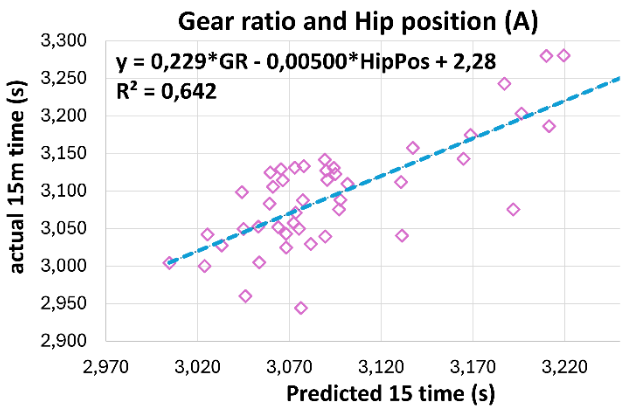


Figure 14 Significant correlations from the multiple regression analysis for cyclist A.

Cyclist B

For cyclist B, the crank length was included in the multiple regression analysis instead of the gear ratio. Although crank length shows a statistically significant correlation with the 15m and 65m split times, none of the multiple regression analyses produced statistically significant results. Both the p-values for the crank length and movement variables exceeded 0.05. Therefore, the correlations between movement variables and the 15m split times, without compensating for crank length, are shown in Table 8.

Table 8 Correlation and significance of movement variables with the 15m split time for cyclist B.

		Cyclist B	
		r	p
Angular velocity hip (deg/s)		0,0417	0,854
Negative angular velocity shoulder (deg/s)		0,0428	0,850
Angular velocity shoulder (deg/s)		-0,0276	0,903
Negative angular velocity knee (deg/s)		0,259	0,245
Angular velocity ankle (deg/s)		0,154	0,495
Negative angular velocity elbow (deg/s)		-0,183	0,415
Angular velocity elbow (deg/s)		-0,152	0,500
Horizontal velocity hip (m/s)		0,249	0,264
Negative hip velocity first stroke (m/s)		-0,0821	0,717
Time above 70% hip velocity (s)		**-0,483**	**0,0229**
Time above 90% hip velocity (s)		-0,194	0,388
Time between peak hip velocity and gate opening (s) – linear		0,265	0,233
Time between peak hip velocity and gate opening (s) - polynomial		0,302	0,403
Distance hip pulled back (cm)		0,129	0,566
Position hip at opening gate (cm)		-0,0560	0,805
Most forward position hip (cm)		-0,136	0,546
Horizontal velocity shoulder (m/s)		**0,439**	**0,0411**
Horizontal velocity elbow (m/s)		0,0559	0,805
Horizontal velocity knee (m/s)		-0,144	0,522
Vertical velocity hip (m/s)		**-0,529**	**0,0113**
Time above 70% hip velocity (s)	**65m**	**-0,619**	**0,00127**
Time above 70% hip velocity (s)	125m	-0,385	0,346
Horizontal velocity shoulder (m/s)	65m	0,331	0,115
Horizontal velocity shoulder (m/s)	125m	-0,0849	0,842
Vertical velocity hip (m/s)	**65m**	**-0,685**	**0,000222**
Vertical velocity hip (m/s)	125m	-0,187	0,657
Multiple Regression Analysis		$P_{shoulder}$	P_{hip}
Maximum horizontal velocity shoulder and hip (m/s)		0,0953	0,937

The maximum horizontal velocity of the shoulder, the maximum vertical velocity of the hip, and the time spent above 70% of the maximum hip velocity are statistically significant for cyclist B (see Figure 15). None of these significant movement variables negatively impact the 65m or 125m split times. The multiple regression analysis indicates that the maximum horizontal velocities of the hip and shoulder are not significantly related to the 15m time.

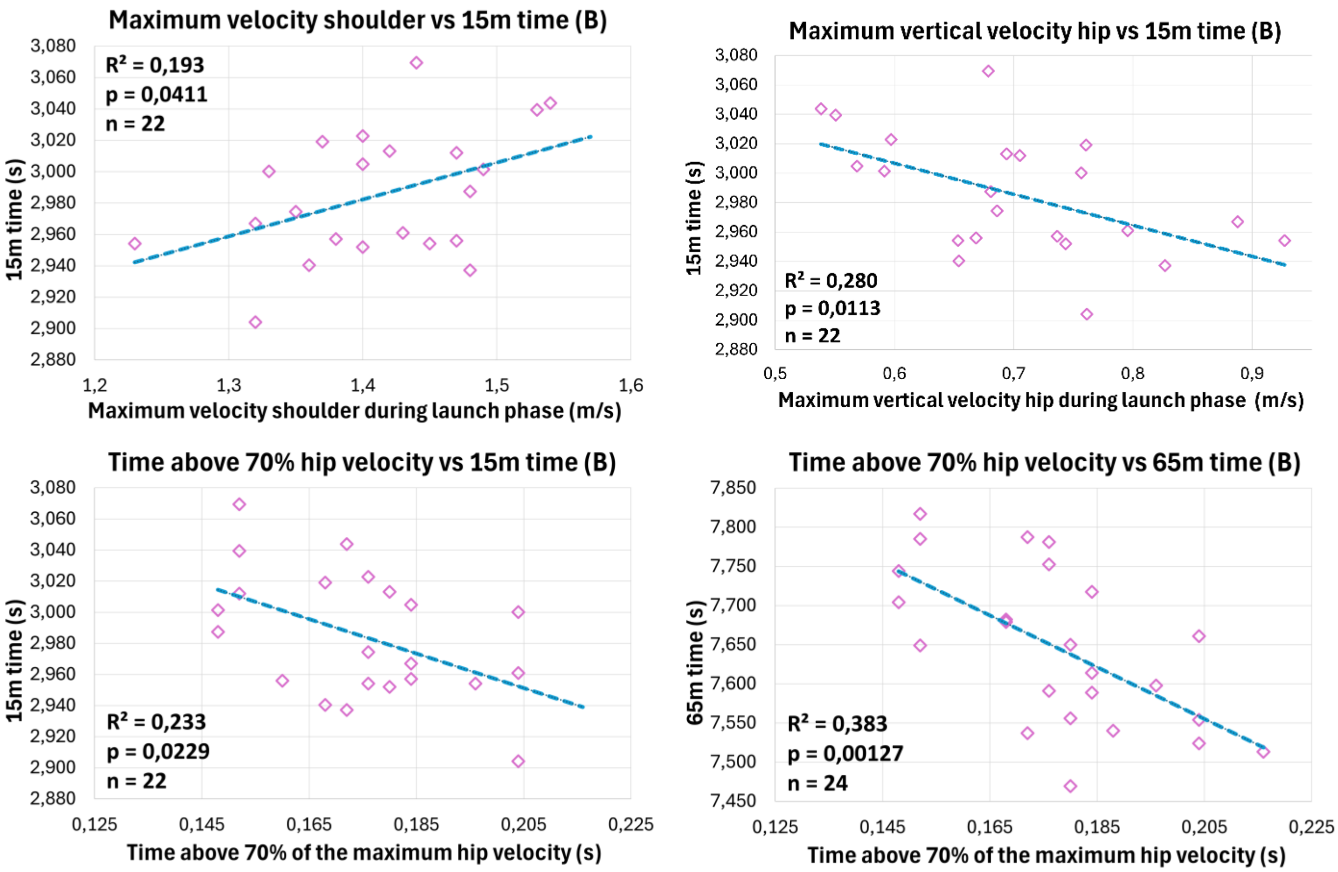


Figure 15 Significant correlations between the movement variables and the split times for cyclist B.

3.1.2. Results for different crank lengths – Cyclist B

170mm crank results

The data set using a 170mm crank reveals three significant movement variables (Figure 16). The maximum angular velocity of the ankle and the maximum velocity of the elbow are significantly correlated with the 15m split time. These movement variables account for 32–36% of the variation in the split times.

Table 9 shows the correlation coefficient and the significance of the movement variables that significantly correlate with the 15m split time, as well as with the 65m and 125m split times. The angular velocity of the hip and the maximum elbow velocity do not negatively affect the longer split times.

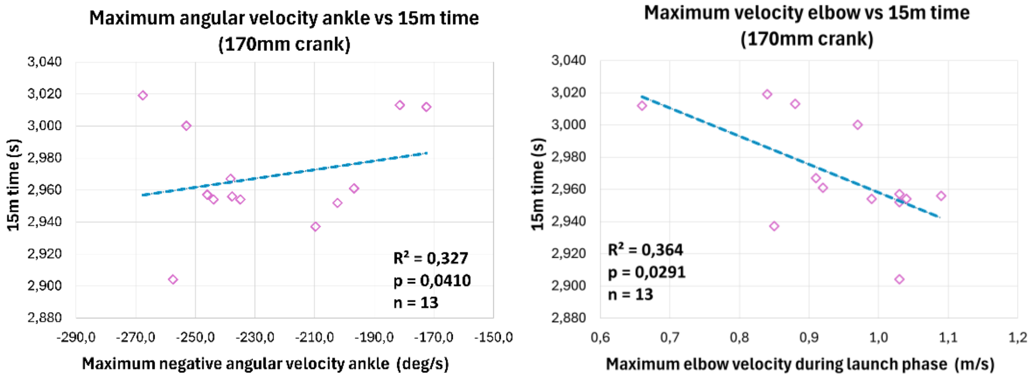


Figure 16 The best correlations between the movement variables and the split times for the trials with a crank length of 170mm.

Table 9 Correlation coefficients and significance of the significant movement variables.

	65m		125m	
	r	p	r	p
Angular negative velocity ankle (deg/s)	0,481	0,113	-0,0147	0,978
Maximum velocity elbow (m/s)	0,350	0,264	0,533	0,276

165mm crank results

For the data set using a 165mm crank, there is only one variable which significantly correlates with the 15m split time: the time between the maximum horizontal hip velocity and the moment the gate opens (Figure 17). When looking at the correlation of this variable with the 65m split time, there is no significant correlation (r = -0,00786; p = 0,981) and for the 125m split time, only two data points are available. Testing this correlation with a second-order polynomial correlation produced an insignificant result (p = 0,143).

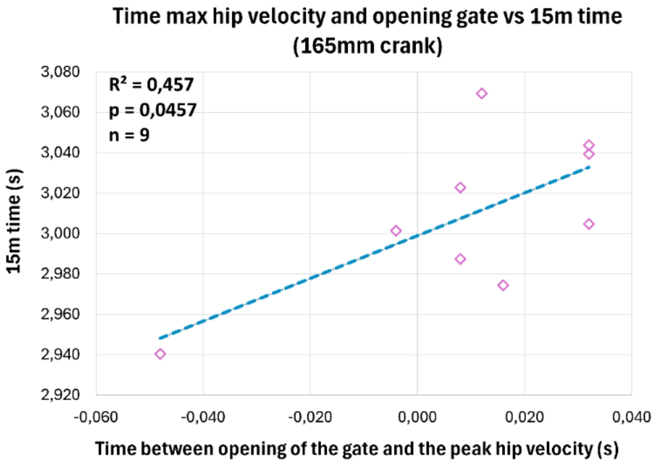


Figure 17 Correlations of the best movement predictors for the 15m- and 65m split time for the dataset with a crank length of 165mm.

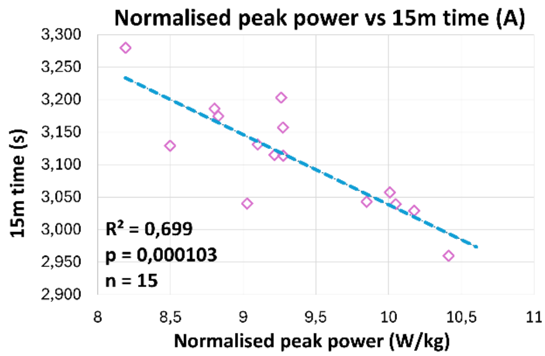
3.2. Power data results

3.2.1. Power versus starting time

The correlations between the power variables tested and the 15m split time are displayed in Table 10. When a variable is significantly correlated with the 15m split time, the correlation coefficients are also displayed for the 65m and 125m split times. For Cyclist B, none of the variables show statistically significant correlations with split times. For Cyclist A, the normalised peak power shows a strong negative correlation, which is statistically significant for both the 15m and 65m split times. The time above 70% of the torque peak in the first pedal stroke also shows a strong, significant correlation with all the split times. Figure 18 also illustrates the significant correlations.

Table 10 Correlation between power data and 15m split time (Pearson's correlation coefficient (r), significance (p), and number of data points (n)).

			r	p	n
Cyclist A	Normalised peak torque		0,468	0,0788	15
	Time to maximum torque		0,322	0,0811	18
	Normalised peak power	15m	**-0,836**	**0,000103**	**15**
		65m	**-0,802**	**0,000561**	**14**
		125m	-0,781	0,119	5
	Time to maximum power		0,315	0,203	18
	Time above 70% max torque	15m	**0,555**	**0,0168**	**18**
		65m	**0,737**	**0,000736**	**17**
		125m	**0,838**	**0,0375**	**6**
	Time above 90% max torque		0,0294	0,908	18
	Crank angle range 70% torque		-0,147	0,560	18
	Crank angle range 90% torque		-0,384	0,116	18
Cyclist B	Normalised peak torque		-0,185	0,545	13
	Time to maximum torque		0,434	0,138	13
	Normalised peak power		-0,102	0,740	13
	Time to maximum power		0,181	0,553	13
	Time above 70% max torque		0,343	0,251	13
	Time above 90% max torque		0,145	0,657	13
	Crank angle range 70% torque		0,0449	0,884	13
	Crank angle range 90% torque		-0,0596	0,847	13



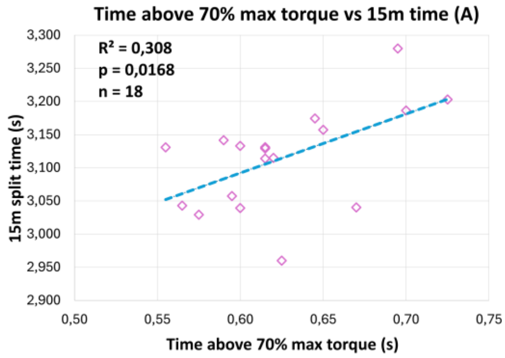


Figure 18 Significant correlation of the power variables with the 15m split time.

3.2.2. Key power variables versus movement variables

Table 11 and Table 12 show Pearson's correlation coefficients and significance of the significant power variables from Section 3.2.1, and all the movement variables. This provides insights into which movements are coupled with the power output. Even though none of the power variables were significant for cyclist B, the table for cyclist B is still included to see if the same correlations appear.

For Cyclist A, the normalised peak power is significantly correlated with the horizontal velocity of the shoulder and the vertical velocity of the hip. These are the same correlations found in the multiple regression analysis with the 15m split time (Section 3.1.1). For cyclist B, these correlations are not significant. However, for Cyclist B, the horizontal velocity of the hip and the angular velocity of the knee are significantly correlated with peak power. Note that the angular velocity of the knee is not available for Cyclist A. Finally, the most forward position of the hip is significantly correlated with peak power for Cyclist B.

The maximum horizontal velocity of the shoulder is also correlated with the time above 70% of peak torque for Cyclist A. For Cyclist B, the angular velocity of the knee is also related to the time above 70% of peak torque.

Table 11 Correlations between the key power variables and the movement variables for cyclist A

Cyclist A	**Normalised peak power**		**Time above 70% peak torque**	
	r	p	r	p
Angular velocity hip (deg/s)	0,341	0,181	-0,131	0,583
Negative angular velocity hip (deg/s)	0,0130	0,961	-0,303	0,194
Negative angular velocity shoulder (deg/s)	-0,462	0,0618	**0,493**	**0,0272**
Angular velocity shoulder (deg/s)	0,123	0,637	0,137	0,564
Angular velocity ankle (deg/s)	0,322	0,284	-0,264	0,322
Negative angular velocity elbow (deg/s)	-0,0557	0,832	-0,0680	0,776
Angular velocity elbow (deg/s)	-0,221	0,394	-0,0256	0,915
Horizontal velocity hip (m/s)	0,161	0,538	-0,425	0,0615
Negative hip velocity first stroke (m/s)	0,313	0,222	-0,419	0,0660

	Normalised peak power		*Time above 70% peak torque*	
Time above 70% hip velocity (s)	0,354	0,164	0,116	0,625
Time above 90% hip velocity (s)	0,0695	0,791	**0,470**	**0,0366**
Time between peak hip velocity and gate opening (s)	0,169	0,518	-0,0961	0,687
Distance hip pulled back (cm)	-0,285	0,268	**0,469**	**0,0369**
Position hip at opening gate (cm)	-0,0156	0,953	0,281	0,230
Most forward position hip (cm)	-0,0897	0,732	**0,516**	**0,0197**
Horizontal velocity shoulder (m/s)	**0,587**	**0,0132**	**-0,528**	**0,0167**
Horizontal velocity elbow (m/s)	-0,0143	0,957	0,0630	0,792
Horizontal velocity knee (m/s)	-0,0901	0,731	-0,0612	0,798
Vertical velocity hip (m/s)	**0,575**	**0,0157**	-0,316	0,175

Table 12 Correlation between the power and movement variables

Cyclist B	**Normalised peak power**		**Time above 70% peak torque**	
	r	p	r	p
Angular velocity hip (deg/s)	-0,203	0,506	-0,374	0,208
Negative angular velocity shoulder (deg/s)	0,140	0,648	0,306	0,309
Angular velocity shoulder (deg/s)	-0,221	0,469	-0,00468	0,988
Angular velocity knee(deg/s)	**0,556**	**0,0485**	**0,675**	**0,0114**
Angular velocity ankle (deg/s)	-0,200	0,512	0,481	0,0961
Negative angular velocity elbow (deg/s)	0,0329	0,915	0,553	**0,0502**
Angular velocity elbow (deg/s)	-0,222	0,465	**-0,710**	**0,00657**
Horizontal velocity hip (m/s)	**-0,686**	**0,00966**	-0,268	0,376
Negative hip velocity first stroke (m/s)	0,407	0,168	0,357	0,231
Time above 70% hip velocity (s)	0,0190	0,951	**-0,525**	**0,0652**
Time above 90% hip velocity (s)	0,300	0,319	-0,147	0,632
Time between peak hip velocity and gate opening (s)	0,0462	0,881	-0,494	0,0859
Distance hip pulled back (cm)	-0,275	0,362	**-0,697**	**0,00807**
Position hip at opening gate (cm)	-0,391	0,186	0,0910	0,767
Most forward position hip (cm)	**-0,665**	**0,0132**	-0,393	0,183
Horizontal velocity shoulder (m/s)	0,0466	0,880	0,234	0,441
Horizontal velocity elbow (m/s)	-0,192	0,530	-0,369	0,214
Horizontal velocity knee (m/s)	-0,361	0,225	-0,372	0,211
Vertical velocity hip (m/s)	-0,125	0,684	-0,332	0,267

4. Discussion

4.1. Objectives and major findings

The main aim of this study was to gain insight into how the standing start is influenced by the movement of the cyclist. Additionally, the study aimed to identify other key factors and compare their impact with that of the key movement factors. To assess how good a start was, the 15m split time was used. The faster the 15m split time, the better the start; however, the 65m and 125m split times should not be negatively affected by the key factor leading to the fast 15m split time.

4.1.1. General factors influencing 15m split time

Before examining the correlation between the 15m split time and the movement variables, the effect of the gear ratio and the length of the crank on the 15m time was studied. It was found that the gear ratio had a significant impact on the starting time for Cyclist A, explaining over 55% of the variation in the split time. Choosing the correct gear ratio is thus important for a good start. In this study, the lower the gear ratio for Cyclist A, the faster the split times (15m, 65m, and 125m). One would expect that when the gear ratio is very low, the 65m and 125m split times would slow down, but within the range of gear ratios tested in this study, this was not the case. This can be explained by the fact that Cyclist A uses a gear ratio of 3,65 in competition, and the lowest gear ratio in this study is 3,42, which is quite close to that.

The findings suggest that Cyclist A could benefit from using a lower gear ratio. However, to determine the optimal gear ratio, it would be necessary to analyse the 250m split time and examine how the gear ratio affects performance over this distance. Since the ultimate goal of the starting rider is to cover 250m in the shortest time. A more detailed explanation of the effect of the gear ratio and why it does not have a significant impact on the split times for Cyclist B can be found in Section 4.1.3.

For Cyclist B, the length of the crank is significantly correlated with the 15m split time. The longer the crank arm, the faster the split times. This was counterintuitive, as in competition, the shorter crank arm yielded better results. Using the crank length and a movement variable as independent variables in a multiple regression analysis (MRA) showed that the crank length was not a good predictor for the 15m time, as it did not provide any significant results, with p-values ranging from 0,65 to 0,91 for almost all the analyses. One explanation is that the crank length coincides with another significant variable. Table 13 shows the correlation between the crank length and the movement variables. Interestingly, the crank length shows a significant correlation with the horizontal velocity of the shoulder, and the horizontal velocity of the shoulder is significantly correlated with the 15m split time for Cyclist B. However, the crank length is not expected to have an impact on the velocity of the shoulder, so this suggests that the correlation is coincidental.

Table 13 Correlation between the crank length and the movement variables.

Cyclist B	**Crank length**	
	r	p
Angular velocity hip (deg/s)	0,0676	0,728
Negative angular velocity shoulder (deg/s)	-0,159	0,409
Angular velocity shoulder (deg/s)	**0,470**	**0,0100**
Negative angular velocity knee (deg/s)	0,0889	0,647
Angular velocity ankle (deg/s)	0,128	0,508
Negative angular velocity elbow (deg/s)	0,313	0,0986
Angular velocity elbow (deg/s)	-0,0693	0,721
Horizontal velocity hip (m/s)	-0,222	0,247
Negative hip velocity first stroke (m/s)	0,278	0,144
Time above 70% hip velocity (s)	0,299	0,115
Time above 90% hip velocity (s)	0,155	0,421
Time between peak hip velocity and gate opening (s)	-0,297	0,117
Distance hip pulled back (cm)	0,0324	0,868
Most forward position hip (cm)	0,186	0,335
Horizontal velocity shoulder (m/s)	**-0,420**	**0,0232**
Horizontal velocity elbow (m/s)	**-0,474**	**0,00947**
Horizontal velocity knee (m/s)	-0,127	0,511
Vertical velocity hip (m/s)	0,345	0,0667

4.1.2. Validity significant movement variables

The optimal movement of the cyclist during the start was expected to involve the cyclist moving the hip all the way back before the gate opens, and then explosively throwing the hip and shoulders forward to achieve a high maximum horizontal velocity of the hip and shoulders when the bike is released from the starting gate. This theory was tested using the following two hypotheses:

1. *The more explosively the cyclist accelerates their body forward, as seen in the maximum horizontal velocity of the hip and shoulder during the start, the faster the starting time, shown in the 15m split time.*
2. *The better the timing of the acceleration of the hip, the lower the 15m split time.*

One would expect a significant linear correlation between the maximum horizontal velocity of the hip and/or shoulder and the 15m split time, and one would expect to see a significant second-order polynomial correlation for 'the time between the maximum hip velocity and the opening of the gate' and the 15m split time, where the lower the time between the peak hip velocity and the opening of the gate, the lower the 15m split time, as a lower time means that the peak hip velocity is achieved at the exact same moment as the gate opens.

The maximum horizontal velocity of the shoulder in the MRA for cyclist A is almost significantly correlated with the 15m time (p = 0,0511). When the maximum velocity of the shoulder and hip, along with the gear ratio, are used to predict the 15m time, the maximum velocity of the shoulder is significant (p = 0,0404), but the maximum velocity of the hip is not significant in this prediction (p = 0,255). The correlation is as expected: the higher the maximum velocity of the shoulder, the faster the 15m time. However, the general analysis for cyclist B, Section 3.1.1, shows a significant, positive correlation between the maximum horizontal velocity of the shoulder and the 15m time, such that the faster the shoulder, the slower the 15m time.

For cyclist A, there is also a significant, positive correlation between the maximum horizontal velocity of the shoulder and the normalised peak power, meaning that the higher the peak velocity of the shoulder, the higher the peak power and the faster the 15m time. An explanation for this could be a difference in technique, possibly due to body type. Cyclist B focuses on explosively moving the hip forward, while cyclist A focuses on moving both the hip and shoulder forward.

In the general analysis of cyclist B, the time above 70% of the maximum hip velocity is negatively and significantly correlated with the 15m and 65m split times, meaning the longer the hip velocity is above 70% of the maximum, the faster the split times. On the other hand, the maximum horizontal hip velocity is negatively correlated with the normalised peak power, indicating that the higher the velocity of the hip, the lower the power peak. The latter suggests a trade-off between power production and moving the hip. When the hip moves faster, there is less time to produce power in that pedal stroke, and the peak might be lower. Overall, the results for cyclist B seem to conflict and the correlation between the 15m split time and the time above 70% of the maximum hip velocity seems to be a coincidence, as other variations of the hip velocity, such as 90% above peak hip velocity, do not show any significant correlation. Therefore, based on the results, hypotheses 1 and 2 are rejected.

Another theory is that the cyclist's movement purely facilitates the maximum power output by positioning the body in the most mechanically advantageous position with respect to the pedals. This theory is reflected in the third hypothesis: *the optimal movement for the start is the one that leads to the highest power output during the first pedal stroke (3)*. Before examining the movement variables, it is useful to check if the power data itself shows significant correlations with the 15m time. Only for cyclist A does the power data show significant correlations, specifically the normalised peak power during the first pedal stroke and the time above 70% of peak torque. A detailed discussion of the power data can be found in Section 4.3.

The position of the hip is expected to be a key factor in power production, as it determines the position of the lower body relative to the pedals. One would expect a second-order polynomial correlation for 'the position of the hip with respect to the saddle at the opening of the gate', with an optimal distance somewhere in the middle of the dataset. For cyclist A, the position of the hip at the opening of the gate was only linearly, significantly correlated with the 15m split time ($p = 0{,}0224$). For cyclist B, this correlation was not significant. The correlation seems a coincidence.

A variable that is significant for cyclist B, and can also be related to the third hypothesis and the power data is the maximum vertical hip velocity. The correlation is negative, meaning that the higher the maximum vertical hip velocity, the faster the 15m time. One would expect only the horizontal movements to have a significant impact, as they generate momentum in the direction of travel, but this variable could be an indication of how fast the hip is pulled back between the first and second downstroke of the pedals. For cyclist A, the maximum vertical hip velocity is significantly and positively correlated with the normalised power peak. This suggests that the faster the hip moves upwards, the more power the cyclist produces. Thus, the vertical movement of the hip contributes to higher power output. An explanation could be that when the cyclist's core is under tension and they pull on the handlebars, the faster extension of the leg leads to a higher power output. Therefore, by 'resetting' the hips faster for the second downstroke, the cyclist can push harder against the pedals. Hypothesis 3 could be partly right, as the power seems to play an important role, but the movement on itself does not give any useful information, as the core tension and the muscle forces are also important in the power production.

Within the separate data sets for the different crank lengths for cyclist B, a few new variables begin to correlate with the 15m split time. These include the angular velocity of the ankle and the maximum horizontal velocity of the elbow for the 170mm crank, and the time between the peak velocity of the hip and the opening of the gate for the 165mm crank data set. There is not necessarily a clear explanation for why the ankle or the horizontal velocity of the elbow should be important, other than the fact that the elbow moves with the whole body and the ankle might play a role in power production.

The time between the peak hip velocity is expected to have a second-order polynomial correlation but only shows a linear correlation. This is likely due to an outlier where the peak hip velocity was achieved before the opening of the gate, and this time was faster. It is important to note that the 170mm dataset consists of only 13 15m split times, and the 165mm dataset contains only 9 15m split times, which increases the uncertainty of the correlations.

4.1.3. Validity gear ratio and power data results

The relationship between gear ratio and split times shows a strong, positive, statistically significant correlation for Cyclist A. Dunst and Grüneberger demonstrated that there is an optimal gear ratio for each race distance. If the gear ratio is too low, the cyclist will fatigue quickly, while if it is too high, the cyclist may reach top speed later or not at all (Dunst & Grüneberger, A Novel Approach of Modelling and Predicting Track Cycling Sprint Performance, 2021). Typically, one would expect a second-order polynomial correlation between gear ratio and split time, but since the lowest gear ratio Cyclist A used is close to her competition ratio, it is likely near her optimal gear ratio. The data shows that a smaller gear ratio tends to result in faster split times at 15m, 65m, and 125m, as top speed is not reached in the early part of the lap. A second-order polynomial relationship would likely appear with significantly smaller gear ratios, as the cyclist would quickly reach high cadence and fatigue prematurely.

For Cyclist B, the correlation between gear ratio and split times is not statistically significant, likely because the range in gear ratios used was small. With less variation in gear ratios, other factors may have more influence on split times. The best correlation was seen for the 125m split time, but with only 8 measurements and considerable variation, the p-value remained above 0.05. As such, this study does not show a statistically significant correlation between gear ratio and split times for Cyclist B.

Kordi and Van Rijswijk report a strong, negative correlation between normalised peak torque of the leading leg and split times, as well as between normalised peak power output and split times (Kordi & Van Rijswijk, 2024). In this research, only Cyclist A shows a statistically significant negative correlation between normalised peak power and the 15m and 65m split times. Normalised peak torque does not show significant correlations for either cyclist and normalised peak power does not significantly correlate with split times for Cyclist B. The lack of correlation between normalised peak power and the 125m split time may be due to the limited number of data points (only five).

Rylands et al. showed a statistically significant correlation between peak power output and gear ratio in BMX cycling. Testing gear ratios of 2.56, 2.69, and 2.81, they found that higher gear ratios produced greater peak power output, although the time to reach peak power was unaffected (Rylands, Roberts, & Hurst, 2017). Similarly, Barnett et al. found that middle-range gear ratios produced the highest peak power output. Their study showed that the two largest gear ratios resulted in significantly longer times to reach maximum torque (Barnett, Jenkins, & Mackinnon, 1996). In the present study, time to maximum torque and time to peak power show no significant correlation with gear ratio. The lack of correlation for Cyclist B can be attributed to the small range of gear ratios used, similar to Rylands' findings. The significant correlation for the 65m split time in Cyclist A could be due to insufficient data for the 125m split time or the limited range of gear ratios used, as Barnett's study suggests.

The question remains as to why peak torque does not correlate with split times and why peak power only correlates with split times for Cyclist A. One reason could be that since gear ratio correlates with peak power, the limited variation in gear ratios for Cyclist B results in little variation in peak power, making the data more sensitive to measurement uncertainties. Additionally, there may not have been enough power data to eliminate coincidences and obtain statistically significant correlations. For the 65m and 125m split times, fatigue from earlier starts in the session could also play a role. Peak torque and power during the first power stroke are less affected by fatigue, as they occur almost instantaneously. Lastly, no studies were found that directly correlate peak torque with split times, so it is possible that peak torque is not useful for predicting split times, as it is dependent on the gear ratio. Many studies suggest that optimal power and torque depend on cadence (Martin, Wagner, & Coyle, 1997) (Dorel, et al., 2005) (Dorel S. , 2018), and this optimal cadence can shift with fatigue (Dunst & Grüneberger, A Novel Approach of Modelling and Predicting Track Cycling Sprint Performance, 2021) (Dunst, Grüneberger, & Holmberg, Modeling Optimal Cadence as a Function of Time during Maximal Sprint Exercises Can Improve Performance by Elite Track Cyclists, 2021).

The only angular velocity showing a relationship with power data is the knee for Cyclist B. The maximum angular velocity of the knee is significantly correlated with the normalised peak power and the time above 70% of maximum torque. The lack of a similar relationship for Cyclist A could be due to the fact that the trailing leg was on the side facing the camera, whereas Cyclist B's leading leg was captured. Mehdi et al. found a significant relationship between peak power output and the knee extensors ($r = 0.71$) and knee flexors ($r = 0.53$) (Kordi, Goodall, Barratt, Rowley, & Leeder, 2017). Based on this study, one might expect hip and knee movements to strongly correlate with power output, however, Mehdi et al. do not mention angular velocity specifically, nor what kind of relationship should be expected. Since joint power is the product of joint torque and angular velocity (Turpin & Watier, 2020), it is reasonable to expect a correlation between joint angular velocity and power output, but in this study, only the maximum angular velocity of the knee correlates only with normalised torque, not normalised power. This may be because total output power and torque are the result of combined contributions from all joints, so the power or torque of a single joint may not predict overall output. Interestingly, higher negative angular velocities of the knee correspond to lower torque output. While there is no sprint cycling literature on this, Hahn, Herzog, and Schwirtz (2014) showed that joint torque decreases with increasing angular velocity during knee flexion, which aligns with the findings of this study (Hahn, Herzog, & Schwirtz, 2014).

Finally, there are some other variables that significantly correlate with the normalised peak power and the time above 70% of peak torque. These variables mainly include the distance the hip is pulled back and the most forward position of the hip during the first pedal stroke. This is not an obvious correlation and is probably caused by the uncertainty of the movement variables, as discussed in Section 4.2.1.

4.2. Limitations

4.2.1. Accuracy movement variables

In general, several factors affect the accuracy of movement variables, most of which stem from uncertainties in tracking the markers. First, the camera was not always perfectly parallel to the plane of movement. Additionally, the fence to which the camera was attached could move easily if someone walked by or leaned against it, causing minor vibrations in the video.

The markers themselves were sometimes difficult to track. Tracking was based on colour, and the knee marker, in particular, did not perform well. Reflections from surrounding light made the marker appear the same colour as the skin at certain angles, resulting in a shaky path that had to be manually corrected. However, some vibrations remained. As the marker has a uniform colour, the tracker could move around within the 3x3 cm area, further contributing to uncertainty in the results. Without filtering, the maximum deviation could be 3 cm for 0,02 seconds, creating velocity peaks of 1,5 m/s. For angular velocities, accuracy depends on tracking three markers, tripling the uncertainty compared to linear velocities.

Another challenge was ensuring the markers were placed in exactly the same spot for each session. For cyclist A, this was solved by painting markers on the suit, but this was not possible for cyclist B, so the markers had to be reapplied each session.

Another issue was that the bike was not always perfectly aligned in the machine, making it difficult to define the line of horizontal movement in Kinovea. If the direction of movement is not perfect, the horizontal movement values become smaller while the vertical values increase slightly. Additionally, Kinovea's pixel-to-centimetre conversion line introduces some uncertainty. Minor variations in how this line is defined lead to different conversion values. To minimise this effect, a long line of over 3 metres was used for the conversion.

4.2.2. Accuracy timing and split times

In general, the accuracy of the split times is influenced by several factors. First, the timing is subtracted from the split times to capture only the time of movement. The accuracy of this timing depends on when the LED lights up and when the bike starts moving. These times are determined using video data with a frame rate of 250 fps, meaning the time between frames is 0,004 seconds. The moment the bike begins to move can be difficult to pinpoint, as its initial movement is very small within the 0,004-second timeframe. Additionally, there is further uncertainty due to slight camera movements caused by people walking by or leaning on the fence where the tripod is mounted. This could result in an error of 2 or 3 frames in identifying the exact moment the bike starts moving, which equates to an uncertainty of 0,012 seconds.

A larger factor affecting timing accuracy is when the LED lights up, which does not always coincide with the moment the gate opens. The acceleration of the cylinders that release the bike's rear wheel is inconsistent, as the pressure varies between starts. This inconsistency is partly due to an air hose leak. When the acceleration is insufficient, the threshold is not reached, and the LED only lights up when the cylinders decelerate because this is a more sudden stop. The Arduino registers the absolute value of accelerations, so both acceleration and deceleration can trigger the LED. On average, the cylinders decelerate 0,8 seconds after the gate opens, introducing significant uncertainty in the timing. If the LED lights up after the bike starts moving, the timing is obtained by observing the cylinder's movement in the video, but this can be hard to spot, resulting in an additional uncertainty of approximately 5 frames, equivalent to 0,02 seconds. This brings the total timing uncertainty from 0,812 seconds down to 0,032 seconds.

Secondly, the distance to the red line is subtracted from the split times to correct for the different starting machine positions. By subtracting this distance, all split times are made comparable over the same distance. The distance to the red line is measured with an accuracy of 5 mm, as identifying the centre of the wheel on the ground with higher precision in the short time one has before the start is challenging. Besides the uncertainty in the measured distance, another factor is the conversion from this distance to the time taken to cover it. For simplicity, it is assumed that the rider is travelling at approximately the same speed and covers the additional centimetres at a constant velocity. The velocity for 5 trials was calculated for each rider, and the average was used to determine the additional time. On average, the additional distance was 20,3 ± 3,3 cm for cyclist A and 8,7 ± 3,0 cm for cyclist B. A difference of 0,5 m/s results in a time difference of 0,0015 s, while a 5 mm distance difference results in a time difference of 0,0007 s. Assuming the variation in velocity between trials remains within 0,5 m/s and the distance difference within 5 mm, the accuracy of the additional time is 0,0022 s.

To equalise the split times for differences in mass and air density between sessions, the additional time this adds to the split times is approximated using a model. The velocity profile is calculated using the angular velocity of the crank, the gear ratio, and the circumference of the wheel. The angular velocity did change stepwise, leading to spikes in the velocity profile, which had to be filtered. The circumference of the wheel was only measured once and only noted with an accuracy of ± 0,5 cm. The power data was not available for all the trials, so a velocity profile from another trial was used to calculate the additional time. This leads to errors because the velocity profile between trials is not exactly the same. To minimise the error, a velocity profile was chosen from a trial with the same gear ratio, and the difference in split times was also minimised. The model is also simplified and only the air and rolling resistance were taken into account, whereas in reality, drivetrain efficiency and changes in track height should also be considered. The assumption that the power output of the cyclist remains the same was also not tested for validity. Finally, there were several scenarios where the new velocity profile was unstable and increased exponentially. To fix this, an extra condition was added to ensure that the velocity change between two time points (0,005 seconds) could not be greater than 0,05 m/s. This can, of course, influence the velocity profile, but it is plausible that the changes in velocity are not greater for such a small time period, and by visually inspecting the velocity profile while tuning this threshold, it was ensured that there were no large differences.

For some trials, the time data were unavailable. In these cases, the time data were obtained from a video recorded on a phone with a frame rate of 50 fps. The moment the front fork crosses the split line can be determined within a frame, giving these split times an uncertainty of 0,02 s.

Finally, sometimes the bike is not positioned straight in the machine, or the cyclist swerves instead of riding in a perfectly straight line. It is difficult to determine how much extra distance the cyclist covers and the exact additional uncertainty for the split times. The cyclist may also not follow the black datum line, which indicates the shortest route around the track, adding more uncertainty. For example, if the cyclist rides an extra 10 cm in the first 15 m, this will add 0,013 seconds to the split time. This research did not collect data on the precise line that cyclists followed, so the additional time for not taking the straightest path is unknown. It is likely, however, that there is always some minor swerving and deviation from the datum line, resulting in minimal additional time differences.

4.3. Practical relevance

A good start begins with choosing the right gear ratio. The gear ratio explains between 55 and 93% of the variation in the split times, so optimising the gear ratio, makes the biggest difference. To further improve the start, a cyclist should focus on increasing the normalised peak power output in the first pedal stroke. This decreases the times not only for 15, but also 65 and most likely also 125m. The horizontal velocity of the hip does not make a significant difference in the starting time, so the cyclist should focus moving in a way that they can produce maximum power. It is likely, that the vertical velocity of the hip plays a role in the power production, which shows that it is important to explosively move the hip up between pedal strokes. More research should be done on the vertical movement of the hip and the horizontal movement of the shoulder, but it looks like smaller cyclists probably should focus on explosively moving their shoulders forward, whilst larger cyclists should more focus on throwing the hip forwards, but the data points to the fact that there is probably an optimum between the horizontal velocity of the hip and the peak power output.

5. Conclusion and recommendations

5.1. Findings

The goal of this study was to identify the key factors influencing the standing start in track cycling. The findings highlight that selecting the right gear ratio is crucial for optimising the standing start. The gear ratio accounts for 55-93% of the variation in the split times. The results suggest that the gear ratio should be small enough to enhance initial acceleration without compromising performance over 250m. As the ultimate goal for the starting rider is to complete the 250m as quickly as possible, the optimal gear ratio is the one that yields the fastest 250m split time.

The normalised peak power output during the first pedal stroke was a strong predictor of start performance, explaining 70% of the variation in the 15m starting time and 64% of the variation in the 65m split time. Although a similar trend was observed for the 125m split time, the limited number of data points (n=5) meant the correlation was not statistically significant. Overall, higher power output during the initial pedal stroke corresponds to a faster start, suggesting that peak power output is a reliable indicator of performance in the early phase of the lap.

It was hypothesised that the horizontal velocity of the hip and shoulder would play a significant role in acceleration during the start. However, the findings revealed that hip velocity does not significantly impact the 15m, 65m, or 125m split times. In contrast, the horizontal velocity of the shoulder was a good predictor of starting time, though the correlation was positive for one cyclist and negative for the other. This suggests that the optimal movement of the body is dependent on the body type. The vertical velocity of the hip was also a good predictor explaining 28% of the variation in the starting time. The vertical velocity of the hip supports the power production, as shown by its significant correlation with normalised peak power output.

5.2. Future research

First of all, the optimal gear ratio for each starting rider should be researched. This should be done by looking at the impact of the gear ratio on the 250m split time and the gear ratio leading to the lowest 250m split time is the optimal gear ratio for that rider.

Secondly, the relationship between the normalised power peak during the first pedal stroke and the 125- and 250m split time should be researched to see if a higher peak power output during the first pedal stroke always contributes to a faster starting lap or if there is an optimum. If there is not an optimum, then future research should explore which movements contribute to achieving the highest peak power during the first pedal stroke. The effect of the maximum vertical hip velocity should be the focus, as it shows a significant correlation with the starting time in this study. A method which also captures the muscle forces could aid in researching the optimal motion for the highest peak power output during the first pedal stroke, as it provides insight in the participation of each body part in the power production. An example of this is the Xsens suit (Movella, 2024), which utilises inertial sensors and EMG sensors to capture body motion and muscle forces.

Thirdly, the influence of body type on the starting technique should be researched. This could be done by using two different groups, each consisting of people with roughly the same body type. Then one can see if there are significant differences in technique between those two groups. The main focus should be on the horizontal velocity of the shoulder, as this study showed a contradiction between the horizontal shoulder velocity and for both cyclists this predictor was significant for the starting time.

Finally, another approach to find the influence of the movement of the body would be to test a wider range of movements. Currently, the rider attempts to perform optimally each time, but giving specific instructions—such as moving the hip as little as possible or moving it as quickly as possible—would amplify the effect of each body part's movement. Furthermore, other variables should be controlled as much as possible. An important example is the gear ratio, which has a significant impact on split times. One challenge in this study was the variation in gear ratios, while the cyclist attempted to replicate the same movement each time. When variables that strongly impact split times, such as gear ratios, fluctuate, and movement variables show little variation, it becomes difficult to identify the movement variables that have the most influence on split times.

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Appendix A – Form data collection

Cyclist: ____________ Date: ____________

Environmental parameters	Air pressure (hPa)	Temperature (degrees Celsius)	Humidity (%)
15-min before training			
15-min after training			

At home

- [ ] Obtain training plan from Gert
- [ ] Check battery level and charge camera
- [ ] Check battery level and charge SRM
- [ ] Empty micro-SD for camera
- [ ] Put camera and tripod in backpack
- [ ] Put Arduino and micro-USB in backpack
- [ ] Put laptop and charger in backpack

Before training at velodrome

Put markers on the rider

- [ ] Shoulder
- [ ] Hip
- [ ] Elbow
- [ ] Toe on shoe
- [ ] Below ankle on shoe
- [ ] Knee
- [ ] Bike

- [ ] Secure and align tripod with camera
- [ ] Align camera parallel to the track
- [ ] Secure Arduino and accelerometer to starting machine
- [ ] Open and close gate to test Arduino
- [ ] Connect SRM pedals to smartphone

Check camera settings

- [ ] HFR mode 250 fps
- [ ] Shoot time priority
- [ ] Recording on trigger

- [ ] Measure air pressure, temperature and humidity

Warm up

Description:

Put camera in shooting mode ☐
Measure distance to red led ☐
Measure mass rider with bike ☐

Set 1

Gear ratio: ______

Section	Time	Perceived effort (1-10)	Reason for perceived effort
Start 1			
Rest			
Start 2			
Rest			
Start 3			
Rest			

Set 2

Gear ratio: ______

Section	Time	Perceived effort (1-10)	Reason for perceived effort
Start 1			
Rest			
Start 2			
Rest			
Start 3			
Rest			

Set 3

Gear ratio: ______

Section	Time	Perceived effort (1-10)	Reason for perceived effort
Start 1			
Rest			
Start 2			
Rest			
Start 3			
Rest			

After training

Collect SD with video data: ☐ Collect power data: ☐ Collect MYLAPS splits data: ☐

Collect HRV rider ☐
Measure air pressure, temperature and humidity ☐
Remove Arduino from starting gate ☐
Collect camera and tripod ☐

General notes or comments

Appendix B – Model for calculating additional time changes in mass and air density

```
% Define constants
rho_original = 1.2055; % Original air density (kg/m^3)
rho_new = 1.18; % Adjusted air density (kg/m^3)
Cd = 0.9; % Drag coefficient
A = 0.5; % Frontal area (m^2)
m_original = 72.7; % Original mass (kg)
m_new = 70; % Adjusted mass (kg)
g = 9.81; % Gravitational acceleration (m/s^2)
Cr = 0.0018; % Rolling resistance coefficient

% Load velocity data from CSV file
% CSV uses ';' as the column separator and ',' as the decimal separator
opts = detectImportOptions('c124_250.csv', 'DecimalSeparator', ',', 'Delimiter', ';');
data = readtable('c124_250.csv', opts);

% Extract time and velocity columns
time = data{:, 1}; % Time in seconds
v_original_raw = data{:, 2}; % Velocity in m/s

% Filter the raw velocity data to remove spikes (apply smoothing)
window_size = 15; % Choose a window size for smoothing
v_original = smooth(v_original_raw, window_size);

% Ensure the velocity starts at 0 m/s
v_original(1) = 0;

% Calculate the total power in the original system at each time step
P_original = zeros(size(time));
for i = 1:length(time)
   % Calculate total resistive forces for air and rolling resistance
   F_air = 0.5 * rho_original * Cd * A * v_original(i)^2;
   F_rolling = m_original * g * Cr;

   % Calculate the power in the original system
   P_original(i) = (F_air + F_rolling) * v_original(i);
end

% Initialize the new velocity array
v_new = zeros(size(time));
v_new(1) = v_original(1); % Start with initial velocity at 0 m/s

% Define a maximum change in velocity per time step to stabilise the system (e.g., 0.5 m/s)
max_velocity_change = 0.05; % Maximum allowed velocity change (m/s)
```

```
% Calculate the new velocity profile based on constant power assumption
for i = 2:length(time)
   % Time step
   dt = time(i) - time(i - 1);

   % Calculate the total resistive forces in the new situation (with adjusted air density)
   F_air_new = 0.5 * rho_new * Cd * A * v_new(i-1)^2;
   F_rolling_new = m_new * g * Cr;

   % Use the power from the original situation (P_original) to calculate the new velocity
   P_new = P_original(i-1); % Power is conserved, so it’s equal to the original system power

   % Solve for the new velocity based on the power balance
   v_new(i) = P_new / (F_air_new + F_rolling_new); % New velocity calculated from power
and resistive forces

   % Apply a constraint on the maximum change in velocity
   velocity_change = v_new(i) - v_new(i-1);
   if abs(velocity_change) > max_velocity_change
      % Limit the velocity change to the maximum allowed
      v_new(i) = v_new(i-1) + sign(velocity_change) * max_velocity_change;
   end
end

% Apply additional smoothing to the new velocity profile
v_new_smoothed = smooth(v_new, window_size);

% Calculate distances for original and smoothed new velocity profiles
distance_original = cumtrapz(time, v_original); % Original distance profile
distance_new = cumtrapz(time, v_new_smoothed); % Smoothed adjusted distance profile

% Define target distances
target_distances = [15, 65, 125];

% Correct for non-monotonic values in distance profiles to prevent the
% distance to decrease in time, leading to invalid results or infite
% results
[distance_original_unique, idx_original] = unique(distance_original); % Remove duplicates
time_original_unique = time(idx_original);

[distance_new_unique, idx_new] = unique(distance_new); % Remove duplicates
time_new_unique = time(idx_new);

% Calculate additional time for each target distance
additional_time = zeros(size(target_distances));
for j = 1:length(target_distances)
```

```
    % Find time to reach target distance for original profile
    t_original = interp1(distance_original_unique, time_original_unique, target_distances(j));

    % Find time to reach target distance for smoothed profile
    t_new = interp1(distance_new_unique, time_new_unique, target_distances(j));

    % Compute additional time
    additional_time(j) = t_new - t_original;
end

% Display results
fprintf('Additional time due to increased mass and air density:\n');
for j = 1:length(target_distances)
    fprintf('At %.2f m: %.4f seconds\n', target_distances(j), additional_time(j));
end

% Plot original raw velocity profile (before filtering)
figure;
plot(time, v_original_raw, 'k', 'LineWidth', 2, 'DisplayName', 'Original Raw Velocity'); % Raw
velocity before smoothing
xlabel('Time (s)', 'FontSize', 24, 'FontWeight', 'bold');
ylabel('Velocity (m/s)', 'FontSize', 24, 'FontWeight', 'bold');
legend('Location', 'best', 'FontSize', 20);
title('Velocity Profile Before Filtering', 'FontSize', 36, 'FontWeight', 'bold');
ax = gca; % Get current axis
ax.FontSize = 24; % Increase font size for tick labels
ax.FontWeight = 'bold'; % Make tick labels bold
grid on;

% Plot filtered original velocity and smoothed adjusted velocity
figure;
plot(time, v_original, 'r', 'LineWidth', 2, 'DisplayName', 'Filtered Original Velocity'); % Filtered
velocity
hold on;
plot(time, v_new_smoothed, 'b', 'LineWidth', 2, 'DisplayName', 'Smoothed Adjusted
Velocity'); % Smoothed adjusted velocity
xlabel('Time (s)', 'FontSize', 24, 'FontWeight', 'bold');
ylabel('Velocity (m/s)', 'FontSize', 24, 'FontWeight', 'bold');
legend('Location', 'best', 'FontSize', 20);
title('Velocity Profiles: Filtered Original and Smoothed Adjusted', 'FontSize', 36, 'FontWeight',
'bold');
ax = gca; % Get current axis
ax.FontSize = 24; % Increase font size for tick labels
ax.FontWeight = 'bold'; % Make tick labels bold
grid on;

% Plot original and smoothed adjusted distance profiles
```

```
figure;
plot(time, distance_original, 'r', 'LineWidth', 1.5, 'DisplayName', 'Original Distance');
hold on;
plot(time, distance_new, 'b', 'LineWidth', 1.5, 'DisplayName', 'Smoothed Adjusted Distance');
xlabel('Time (s)');
ylabel('Distance (m)');
legend('Location', 'best');
title('Distance Profiles: Original vs Smoothed Adjusted');
grid on;
```

Appendix C – Calculating air density

Using the Ideal Gas Law (Eq. 4) and the Law of Partial Pressures (Eq. 5), the air density can be calculated using the measured air pressure, temperature, and relative humidity.

$$\rho_{air} = \frac{p}{R * T} \tag{4}$$

$$\rho_{humid,air} = \frac{p_d}{R_d * T} + \frac{p_v}{R_v * T}, \qquad where: \tag{5}$$

$\rho_{humid,air}$ = air density (kg/m^3)
p_d = partial pressure of dry air (Pa) = p – p_v
R_d = specific gas constant for dry air = 287,058 J/(kg*K)
T = temperature (K)
p_v = pressure of water vapor (Pa), calculated with Eq. 6
R_V = specific gas constant for water vapour = 461,495 J/(kg*K)

$$p_v(T) = RH * p_{saturation}, \qquad where: \tag{6}$$

RH = relative humidity
$p_{saturation}$ = saturation vapour pressure (kPa), calculated using Tetens' formula (Eq. 7) for temperatures between 0°C and 30°C (Monteith & Unsworth, 2014).

$$p_{saturation} = 6{,}1078 * 10^{\frac{17{,}27 * T_c}{T_c + 237{,}3}}, \qquad where: \tag{7}$$

T_c = Temperature (degrees Celsius)

Appendix D – Code Arduino

```
#include <Wire.h>
// Registers for ADXL345
#define ADXL345_ADDRESS (0xA6 >> 1)  // address for device is 8 bit but shift to the
                                     // right by 1 bit to make it 7 bit because the
                                     // wire library only takes in 7 bit addresses
#define ADXL345_REGISTER_XLSB (0x32)

int LED = 2;

int accelerometer_data[3];
// void because this only tells the cip to send data to its output register
// writes data to the slave's buffer
void i2c_write(int address, byte reg, byte data) {

  // Send output register address
  Wire.beginTransmission(address);
  // Connect to device
  Wire.write(reg);
  // Send data
  Wire.write(data); //low byte
  Wire.endTransmission();
}

// void because using pointers
// microcontroller reads data from the sensor's input register
void i2c_read(int address, byte reg, int count, byte* data) {
  // Used to read the number of data received
  int i = 0;
  // Send input register address
  Wire.beginTransmission(address);
  // Connect to device
  Wire.write(reg);
  Wire.endTransmission();

  // Connect to device
  Wire.beginTransmission(address);
  // Request data from slave
  // Count stands for number of bytes to request
  Wire.requestFrom(address, count);
  while(Wire.available()) // slave may send less than requested
  {
    char c = Wire.read(); // receive a byte as character
    data[i] = c;
    i++;
  }
```

```
  Wire.endTransmission();
}

void init_adxl345() {
  byte data = 0;

  i2c_write(ADXL345_ADDRESS, 0x31, 0x0B);   // 13-bit mode  +_ 16g
  i2c_write(ADXL345_ADDRESS, 0x2D, 0x08);   // Power register


  i2c_write(ADXL345_ADDRESS, 0x1E, 0x00);   // x
  i2c_write(ADXL345_ADDRESS, 0x1F, 0x00);   // Y
  i2c_write(ADXL345_ADDRESS, 0x20, 0x05);   // Z

  // Check to see if it worked!
  i2c_read(ADXL345_ADDRESS, 0X00, 1, &data);
  if(data==0xE5)
    Serial.println("it work Success");
  else
    Serial.println("it work Fail");
}

void read_adxl345() {
  byte bytes[6];
  memset(bytes,0,6);

  // Read 6 bytes from the ADXL345
  i2c_read(ADXL345_ADDRESS, ADXL345_REGISTER_XLSB, 6, bytes);
  // Unpack data
  for (int i=0;i<3;++i) {
    accelerometer_data[i] = (int)bytes[2*i] + (((int)bytes[2*i + 1]) << 8);
  }
}
// initialise and start everything
void setup() {
  Wire.begin();
  Serial.begin(9600);
  for(int i=0; i<3; ++i) {
    accelerometer_data[i]  = 0;
  }
  init_adxl345();
}



void loop() {
  read_adxl345();
```

```
  if (abs(accelerometer_data[2]) > 200){
    digitalWrite(LED, HIGH);
    Serial.print(float(abs(accelerometer_data[2])));//3.9mg/LSB scale factor in 13-bit mode
    Serial.print("\n");
    delay(3000);
    digitalWrite(LED, LOW);}
  else{}
  Serial.print("ACCEL: ");
  Serial.print(float(abs(accelerometer_data[2])));//3.9mg/LSB scale factor in 13-bit mode
  Serial.print("\n");
  delay(2);


}
```

Appendix E – Code data processing Matlab

Code for plotting linear velocities

```
% Parameters
startnumber = 99; % number of startfile minus 1
endnumber = 113;
num_files = endnumber-startnumber;   % Number of files
fc = 2;         % Cutoff frequency for the Butterworth filter
fs = 50;        % Sampling rate (same as the video frame rate)
n_order = 6;    % Filter order for Butterworth filter

% Define a lot of different colors for plotting the data (one color for each file number)
colors = {'black', 'red', 'green', 'blue',
'magenta','cyan','yellow',"#8A2BE2","#A52A2A","#7FFF00","#FF7F50","#6495ED","#DC143C"
,
'#00008B','#8B008B','#FF8C00','#8FBC8F','#FF1493','#00BFFF','#FFD700','#F0E68C','#3BB9FF'
,'#66CDAA','#01F9C6','#728C00','#F5DEB3','#FFDF00','#F4A460','#C11B17','#3D0C02','#8726
57'};

%% Reading all the .csv files and storing the data
% Initialize arrays to store the data
xhip_all = cell(1, num_files);
xbike_all = cell(1, num_files);
time_all = cell(1, num_files);

% Loop over each file
for i = startnumber:endnumber
   % Construct file names corresponding to the video file numbers
   x_filename = sprintf('c%dxposition.csv', i);
   y_filename = sprintf('c%dyposition.csv', i);

   try
      % Read data
      x_data = readmatrix(x_filename, 'DecimalSeparator', ',', 'Delimiter', ';');
      y_data = readmatrix(y_filename, 'DecimalSeparator', ',', 'Delimiter', ';');

      % Assign variables to arrays and scale them properly. They are stored in centimeters and
here converted to meters.
      xhip = x_data(2:end, 3) .* 0.01; %change the column for different joints. Hip = 3,
shoulder = 4, elbow = 5, hand = 6, knee = 7, ankle = 8, toe = 9
      yhip = y_data(2:end, 3) .* -0.01; %the positive y axis is pointing downwards in Kinovea
so the minus corrects for that.
      xbike = x_data(2:end, 10) .* 0.01;
      ybike = y_data(2:end, 10) .* -0.01;
      time = x_data(2:end, 1) .* 0.0002; %convert from 200Hz data to seconds
      xhiprelative = xhip-xbike;
```

```
        yhiprelative = yhip-ybike;

        % Store data in arrays
        xhip_all{i - startnumber} = xhiprelative; %change here between relative or normal hip
movement. 'xhiprelative' or 'xhip'
        xbike_all{i - startnumber} = xbike;
        yhip_all{i - startnumber} = yhiprelative; %change here between relative or normal hip
movement
        ybike_all{i - startnumber} = ybike;
        time_all{i - startnumber} = time;
    catch
        % Display warning if file is not found or an error occurs
        warning(['Data file for c' num2str(i) ' not found or cannot be read. Skipping to next
file.']);
        continue;  % Skip to the next iteration of the loop
    end
end

%% Filtering and differentiation of the data
%Initialize cell arrays to store the data
xhip_filtered_all = cell(1, num_files);
xbike_filtered_all = cell(1, num_files);
velocity_xhip_all = cell(1, num_files);
acceleration_xhip_all = cell(1, num_files);
yhip_filtered_all = cell(1, num_files);
ybike_filtered_all = cell(1, num_files);
velocity_yhip_all = cell(1, num_files);
acceleration_yhip_all = cell(1, num_files);

for i = 1:num_files
    if isempty(xhip_all{i})
        % Skip processing if the data is empty (display: file was skipped)
        continue;
    end

    % Apply Butterworth filter to the x data of the hip
    [b, a] = butter(n_order, fc / (fs / 2));
    xhip_filtered_all{i} = filtfilt(b, a, xhip_all{i});

    % Calculate velocity (derivative of position)
    velocity_xhip_all{i} = diff(xhip_filtered_all{i}) ./ diff(time_all{i});

    % Calculate acceleration (derivative of velocity)
    acceleration_xhip_all{i} = diff(velocity_xhip_all{i}) ./ diff(time_all{i}(1:end-1));
end

for i = 1:num_files
```

```
    if isempty(yhip_all{i})
        % Skip processing if data is empty (file was skipped)
        continue;
    end

    % Apply Butterworth filter to y data of the hip
    [b, a] = butter(n_order, fc / (fs / 2));
    yhip_filtered_all{i} = filtfilt(b, a, yhip_all{i});

    % Calculate velocity (derivative of position)
    velocity_yhip_all{i} = diff(yhip_filtered_all{i}) ./ diff(time_all{i});

    % Calculate acceleration (derivative of velocity)
    acceleration_yhip_all{i} = diff(velocity_yhip_all{i}) ./ diff(time_all{i}(1:end-1));
end

for i = 1:num_files
    if isempty(xbike_all{i})
        % Skip processing if data is empty (file was skipped)
        continue;
    end

    % Apply Butterworth filter to x data of the bike
    [b, a] = butter(n_order, fc / (fs / 2));
    xbike_filtered_all{i} = filtfilt(b, a, xbike_all{i});

    % Calculate velocity (derivative of position)
    velocity_xbike_all{i} = diff(xbike_filtered_all{i}) ./ diff(time_all{i});

    % Calculate acceleration (derivative of velocity)
    acceleration_xbike_all{i} = diff(velocity_xbike_all{i}) ./ diff(time_all{i}(1:end-1));
end

for i = 1:num_files
    if isempty(ybike_all{i})
        % Skip processing if data is empty (file was skipped)
        continue;
    end

    % Apply Butterworth filter to y data of the bike
    [b, a] = butter(n_order, fc / (fs / 2));
    ybike_filtered_all{i} = filtfilt(b, a, ybike_all{i});

    % Calculate velocity (derivative of position)
    velocity_ybike_all{i} = diff(ybike_filtered_all{i}) ./ diff(time_all{i});

    % Calculate acceleration (derivative of velocity)
```

```
    acceleration_ybike_all{i} = diff(velocity_ybike_all{i}) ./ diff(time_all{i}(1:end-1));
end

%% Calculate the magnitude of the velocity of the hip

% Additional arrays to store total velocities
velocity_total_all = cell(1, num_files);

% Calculate magnitude of the hip velocity
for i = 1:num_files
    if isempty(velocity_xhip_all{i}) || isempty(velocity_yhip_all{i})
        % Skip processing if data is empty (file was skipped)
        continue;
    end

    % Calculate total velocity as the magnitude of the vector
    velocity_total_all{i} = sqrt(velocity_xhip_all{i}.^2 + velocity_yhip_all{i}.^2);
end

% Plotting total velocity of hip
figure;

for i = 1:num_files
    if ~isempty(velocity_total_all{i})
        plot(time_all{i}(1:end-1), velocity_total_all{i}, 'color', colors{i}, 'DisplayName', ['c'
num2str(i+startnumber)]);
        hold on;
    end
end

title('Total velocity of hip in time','FontSize',14,'FontWeight','bold');
xlabel('Time (s)','FontSize',12,'FontWeight','bold');
ylabel('Total velocity of hip (m/s)','FontSize',12,'FontWeight','bold');
legend('show', 'Location', 'best');

%% Plotting horizontal position of the hip (or any other joint)

figure;

for i = 1:num_files
    if ~isempty(xhip_filtered_all{i})
        plot(time_all{i}(1:end-10), xhip_filtered_all{i}(1:end-10), 'color', colors{i}, 'DisplayName',
['c' num2str(i+startnumber)]);
        hold on;
        plot(time_all{i}(1:end-10), xbike_filtered_all{i}(1:end-10), 'color', colors{i},
'DisplayName', ['c' num2str(i+startnumber)]);
        hold on;
```

```
    end
end
title('Horizontal position of hip in time','FontSize',14,'FontWeight','bold');
xlabel('Time (s)','FontSize',12,'FontWeight','bold');
ylabel('Horizontal position of hip (m)','FontSize',12,'FontWeight','bold');
legend('show', 'Location', 'best');
%% Plotting horizontal velocity of hip (or any other joint)

figure;

for i = 1:num_files
    if ~isempty(velocity_xhip_all{i})
        plot(time_all{i}(1:end-1), velocity_xhip_all{i}, 'color', colors{i}, 'DisplayName', ['c'
num2str(i+startnumber)]);
        hold on;
    end
end

title('Horizontal velocity of hip in time','FontSize',14,'FontWeight','bold');
xlabel('Time (s)','FontSize',12,'FontWeight','bold');
ylabel('Horizontal velocity of hip (m/s)','FontSize',12,'FontWeight','bold');
legend('show', 'Location', 'best');

%% Plotting horizontal acceleration of hip (or any other joint)

figure;

for i = 1:num_files
    if ~isempty(acceleration_xhip_all{i})
        plot(time_all{i}(1:end-12), acceleration_xhip_all{i}(1:end-10), 'color', colors{i},
'DisplayName', ['c' num2str(i+startnumber)]);
        hold on;
    end
end

title('Horizontal acceleration of hip in time'),'FontSize',14,'FontWeight','bold';
xlabel('Time (s)'),'FontSize',12,'FontWeight','bold';
ylabel('Horizontal acceleration of hip (m/s^2)'),'FontSize',12,'FontWeight','bold';
legend('show', 'Location', 'best');
```

Code for plotting angular velocities

```
% Parameters
startnumber = 114 % number of startfile minus 1
endnumber = 127  ;
num_files = endnumber-startnumber;   % Number of files
```

```
fc = 2;         % Cutoff frequency for the Butterworth filter
fs = 50;        % Sampling rate (video frame rate = 50fps)
n_order = 6;    % Filter order for Butterworth filter

% Define colors for plotting (one for each file)
colors = {'black', 'red', 'green', 'blue',
'magenta','cyan','yellow',"#8A2BE2","#FF7F50","#6495ED","#DC143C",
'#00008B','#8B008B','#FF8C00','#8FBC8F','#FF1493','#00BFFF','#FFD700','#F0E68C','#3BB9FF'
,'#66CDAA','#01F9C6','#728C00','#F5DEB3','#FFDF00','#F4A460','#C11B17','#3D0C02','#8726
57'};

%%
% Initialize arrays to store data
xhip_all = cell(1, num_files);
yhip_all = cell(1, num_files);
xshoulder_all = cell(1, num_files);
yshoulder_all = cell(1, num_files);
xelbow_all = cell(1, num_files);
yelbow_all = cell(1, num_files);
xhand_all = cell(1, num_files);
yhand_all = cell(1, num_files);
xknee_all = cell(1, num_files);
yknee_all = cell(1, num_files);
xankle_all = cell(1, num_files);
yankle_all = cell(1, num_files);
xtoe_all = cell(1, num_files);
ytoe_all = cell(1, num_files);

xbike_all = cell(1, num_files);
ybike_all = cell(1, num_files);
time_all = cell(1, num_files);

% Loop over each file
for i = startnumber:endnumber
   % Construct file names
   x_filename = sprintf('c%dxposition.csv', i);
   y_filename = sprintf('c%dyposition.csv', i);

   try
      % Read data
      x_data = readmatrix(x_filename, 'DecimalSeparator', ',', 'Delimiter', ';');
      y_data = readmatrix(y_filename, 'DecimalSeparator', ',', 'Delimiter', ';');

      % Assign variables to arrays and convert the data to meters and seconds
      xhip = x_data(2:end, 3) .* 0.01;
      yhip = y_data(2:end, 3) .* 0.01;
      xshoulder = x_data(2:end, 4) .* 0.01;
```

```
yshoulder = y_data(2:end, 4) .* 0.01;
xelbow = x_data(2:end, 5) .* 0.01;
yelbow = y_data(2:end, 5) .* 0.01;
xhand = x_data(2:end, 6) .* 0.01;
yhand = y_data(2:end, 6) .* 0.01;
xknee = x_data(2:end, 7) .* 0.01;
yknee = y_data(2:end, 7) .* 0.01;
xankle = x_data(2:end, 8) .* 0.01;
yankle = y_data(2:end, 8) .* 0.01;
xtoe = x_data(2:end, 9) .* 0.01;
ytoe = y_data(2:end, 9) .* 0.01;

xbike = x_data(2:end, 10) .* 0.01;
ybike = x_data(2:end, 10) .* 0.01;
time = x_data(2:end, 1) .* 0.0002;

xhiprelative = xhip-xbike;
yhiprelative = yhip-ybike;
xshoulderrelative = xshoulder-xbike;
yshoulderrelative = yshoulder-ybike;
xelbowrelative = xelbow-xbike;
yelbowrelative = yelbow-ybike;
xhandrelative = xhand-xbike;
yhandrelative = yhand-ybike;
xkneerelative = xknee-xbike;
ykneerelative = yknee-ybike;
xanklerelative = xankle-xbike;
yanklerelative = yankle-ybike;
xtoerelative = xtoe-xbike;
ytoerelative = ytoe-ybike;


% Store data of all the joints in the arrays. Here it is possible
% to change between absolute movement and movement relative to the
% bike by changing for example 'xhip' to 'xhiprelative'
xhip_all{i - startnumber} = xhiprelative;
yhip_all{i - startnumber} = yhiprelative;
xshoulder_all{i - startnumber} = xshoulderrelative;
yshoulder_all{i - startnumber} = yshoulderrelative;
xelbow_all{i - startnumber} = xelbowrelative;
yelbow_all{i - startnumber} = yelbowrelative;
xhand_all{i - startnumber} = xhandrelative;
yhand_all{i - startnumber} = yhandrelative;
xknee_all{i - startnumber} = xkneerelative;
yknee_all{i - startnumber} = ykneerelative;
xankle_all{i - startnumber} = xanklerelative;
yankle_all{i - startnumber} = yanklerelative;
```

```
        xtoe_all{i - startnumber} = xtoerelative;
        ytoe_all{i - startnumber} = ytoerelative;

        xbike_all{i - startnumber} = xbike;
        ybike_all{i - startnumber} = ybike;
        time_all{i - startnumber} = time;
    catch
        % Display warning if file is not found or error occurs
        warning(['Data file for c' num2str(i) ' not found or cannot be read. Skipping to next
file.']);
        continue;  % Skip to the next iteration of the loop
    end
end

% Perform operations (filtering, differentiation) on stored data
xhip_filtered_all = cell(1, num_files);
yhip_filtered_all = cell(1, num_files);
xshoulder_filtered_all = cell(1, num_files);
yshoulder_filtered_all = cell(1, num_files);
xelbow_filtered_all = cell(1, num_files);
yelbow_filtered_all = cell(1, num_files);
xhand_filtered_all = cell(1, num_files);
yhand_filtered_all = cell(1, num_files);
xknee_filtered_all = cell(1, num_files);
yknee_filtered_all = cell(1, num_files);
xankle_filtered_all = cell(1, num_files);
yankle_filtered_all = cell(1, num_files);
xtoe_filtered_all = cell(1, num_files);
ytoe_filtered_all = cell(1, num_files);

xbike_filtered_all = cell(1, num_files);
ybike_filtered_all = cell(1, num_files);


for i = 1:num_files
    if isempty(xhip_all{i})
        % Skip processing if data is empty (file was skipped)
        continue;
    end

    % Apply Butterworth filter to all the positional data
    [b, a] = butter(n_order, fc / (fs / 2));
    xhip_filtered_all{i} = filtfilt(b, a, xhip_all{i});
    [c, d] = butter(n_order, fc / (fs / 2));
    yhip_filtered_all{i} = filtfilt(c, d, yhip_all{i});
    [e, f] = butter(n_order, fc / (fs / 2));
    xshoulder_filtered_all{i} = filtfilt(e, f, xshoulder_all{i});
```

```
    [g, h] = butter(n_order, fc / (fs / 2));
    yshoulder_filtered_all{i} = filtfilt(g, h, yshoulder_all{i});
    [cc, j] = butter(n_order, fc / (fs / 2));
    xelbow_filtered_all{i} = filtfilt(cc, j, xelbow_all{i});
    [k, l] = butter(n_order, fc / (fs / 2));
    yelbow_filtered_all{i} = filtfilt(k, l, yelbow_all{i});
    [m, n] = butter(n_order, fc / (fs / 2));
    xhand_filtered_all{i} = filtfilt(m, n, xhand_all{i});
    [o, p] = butter(n_order, fc / (fs / 2));
    yhand_filtered_all{i} = filtfilt(o, p, yhand_all{i});
    [q, r] = butter(n_order, fc / (fs / 2));
    xknee_filtered_all{i} = filtfilt(q, r, xknee_all{i});
    [s, t] = butter(n_order, fc / (fs / 2));
    yknee_filtered_all{i} = filtfilt(s, t, yknee_all{i});
    [u, v] = butter(n_order, fc / (fs / 2));
    xankle_filtered_all{i} = filtfilt(u, v, xankle_all{i});
    [w, x] = butter(n_order, fc / (fs / 2));
    yankle_filtered_all{i} = filtfilt(w, x, yankle_all{i});
    [y, z] = butter(n_order, fc / (fs / 2));
    xtoe_filtered_all{i} = filtfilt(y, z, xtoe_all{i});
    [aa, bb] = butter(n_order, fc / (fs / 2));
    ytoe_filtered_all{i} = filtfilt(aa, bb, ytoe_all{i});
end

% initialize cell arrays to store the angles
hip_angles = cell(1, num_files);
shoulder_angles = cell(1, num_files);
elbow_angles = cell(1, num_files);
ankle_angles = cell(1, num_files);
knee_angles = cell(1, num_files);

for i = 1:num_files
    if isempty(xhip_filtered_all{i})
        % Skip processing if data is empty (file was skipped)
        continue;
    end

    num_frames = length(xhip_filtered_all{i});
    hip_angles{i} = zeros(num_frames, 1);
    shoulder_angles{i} = zeros(num_frames, 1);
    elbow_angles{i} = zeros(num_frames, 1);
    knee_angles{i} = zeros(num_frames, 1);
    ankle_angles{i} = zeros(num_frames, 1);

%calculate the angles of the joints for all the frames of the video
    for frame = 1:num_frames
        hip_angles{i}(frame) = calculate_angle(...
```

```
        xshoulder_filtered_all{i}(frame), yshoulder_filtered_all{i}(frame), ...
        xhip_filtered_all{i}(frame), yhip_filtered_all{i}(frame), ...
        xknee_filtered_all{i}(frame), yknee_filtered_all{i}(frame));

      shoulder_angles{i}(frame) = calculate_angle(...
        xelbow_filtered_all{i}(frame), yelbow_filtered_all{i}(frame), ...
        xshoulder_filtered_all{i}(frame), yshoulder_filtered_all{i}(frame), ...
        xhip_filtered_all{i}(frame), yhip_filtered_all{i}(frame));

      elbow_angles{i}(frame) = calculate_angle(...
        xshoulder_filtered_all{i}(frame), yshoulder_filtered_all{i}(frame), ...
        xelbow_filtered_all{i}(frame), yelbow_filtered_all{i}(frame), ...
        xhand_filtered_all{i}(frame), yhand_filtered_all{i}(frame));

      knee_angles{i}(frame) = calculate_angle(...
        xhip_filtered_all{i}(frame), yhip_filtered_all{i}(frame), ...
        xknee_filtered_all{i}(frame), yknee_filtered_all{i}(frame), ...
        xankle_filtered_all{i}(frame), yankle_filtered_all{i}(frame));

      ankle_angles{i}(frame) = calculate_angle(...
        xknee_filtered_all{i}(frame), yknee_filtered_all{i}(frame), ...
        xankle_filtered_all{i}(frame), yankle_filtered_all{i}(frame), ...
        xtoe_filtered_all{i}(frame), ytoe_filtered_all{i}(frame));
    end
end

% Initialize arrays to store joint velocities
hip_angular_velocities = cell(1, num_files);
shoulder_angular_velocities = cell(1, num_files);
elbow_angular_velocities = cell(1, num_files);
knee_angular_velocities = cell(1, num_files);
ankle_angular_velocities = cell(1, num_files);

% Differentiate angles to get velocities
for i = 1:num_files
    if isempty(hip_angles{i})
        % Skip processing if data is empty (file was skipped)
        continue;
    end

    % Calculate time differences
    dt = diff(time_all{i});

    % Differentiate angles to get velocities
    hip_angular_velocities{i} = diff(hip_angles{i}) ./ dt;
    shoulder_angular_velocities{i} = diff(shoulder_angles{i}) ./ dt;
    elbow_angular_velocities{i} = diff(elbow_angles{i}) ./ dt;
```

```
    knee_angular_velocities{i} = diff(knee_angles{i}) ./ dt;
    ankle_angular_velocities{i} = diff(ankle_angles{i}) ./ dt;
end
%% Plotting the angles in time

% Plotting hip angles
figure;
hold on;
for i = 1:num_files
    if isempty(hip_angles{i})
        % Skip processing if data is empty (file was skipped)
        continue;
    end

    plot(time_all{i}, hip_angles{i}, 'DisplayName', ['File ' num2str(i + startnumber) 'Hip angle'],
'Color', colors{i});
    hold on
end
xlabel('Time (s)');
ylabel('Joint Angle (degrees)');
title('Hip joint Angles Over Time');
legend show;
hold off;

% Plotting shoulder angles
figure;
hold on;
for i = 1:num_files
    if isempty(shoulder_angles{i})
        % Skip processing if data is empty (file was skipped)
        continue;
    end

    plot(time_all{i}, shoulder_angles{i}, 'DisplayName', ['File ' num2str(i + startnumber)
'Shoulder angle'], 'Color', colors{i});
    hold on
end
xlabel('Time (s)');
ylabel('Joint Angle (degrees)');
title('Shoulder joint Angles Over Time');
legend show;
hold off;

% Plotting elbow angles
figure;
hold on;
for i = 1:num_files
```

```
    if isempty(elbow_angles{i})
        % Skip processing if data is empty (file was skipped)
        continue;
    end
    plot(time_all{i}, elbow_angles{i}, 'DisplayName', ['File ' num2str(i + startnumber) 'Elbow
angle'], 'Color', colors{i});
    hold on
end
xlabel('Time (s)');
ylabel('Joint Angle (degrees)');
title('Elbow joint Angles Over Time');
legend show;
hold off;

% Plotting knee angles
figure;
hold on;
for i = 1:num_files
    if isempty(knee_angles{i})
        % Skip processing if data is empty (file was skipped)
        continue;
    end

    plot(time_all{i}, knee_angles{i}, 'DisplayName', ['File ' num2str(i + startnumber) 'Knee
angle'], 'Color', colors{i});
    hold on

end
xlabel('Time (s)');
ylabel('Joint Angle (degrees)');
title('Knee joint Angles Over Time');
legend show;
hold off;

%plotting ankle angles
figure;
hold on;
for i = 1:num_files
    if isempty(ankle_angles{i})
        % Skip processing if data is empty (file was skipped)
        continue;
    end

    plot(time_all{i}, ankle_angles{i}, 'DisplayName', ['File ' num2str(i + startnumber) 'Ankle
angle'], 'Color', colors{i});
end
xlabel('Time (s)');
```

```
ylabel('Joint Angle (degrees)');
title('Ankle joint Angles Over Time');
legend show;
hold off;

%% Plotting joint angular velocities over time

% Plotting hip angular velocity
figure;
hold on;
for i = 1:num_files
   if isempty(hip_angular_velocities{i})
      % Skip processing if data is empty (file was skipped)
      continue;
   end
   plot(time_all{i}(2:end), hip_angular_velocities{i}, 'DisplayName', ['File ' num2str(i +
startnumber) ' Hip velocity'], 'Color', colors{i});
end
xlabel('Time (s)');
ylabel('Joint angular velocity (degrees/s)');
title('Hip joint angular velocities over time');
legend show;
hold off;

% Plotting shoulder angular velocity
figure;
hold on;
for i = 1:num_files
   if isempty(shoulder_angular_velocities{i})
      % Skip processing if data is empty (file was skipped)
      continue;
   end
   plot(time_all{i}(2:end), shoulder_angular_velocities{i}, 'DisplayName', ['File ' num2str(i +
startnumber) ' Shoulder velocity'], 'Color', colors{i});
end
xlabel('Time (s)');
ylabel('Joint angular velocity (degrees/s)');
title('Shoulder joint angular velocities over time');
legend show;
hold off;

% Plotting elbow angular velocity
figure;
hold on;
for i = 1:num_files
   if isempty(elbow_angular_velocities{i})
      % Skip processing if data is empty (file was skipped)
```

```
        continue;
    end
    plot(time_all{i}(2:end), elbow_angular_velocities{i}, 'DisplayName', ['File ' num2str(i +
startnumber) ' Elbow velocity'], 'Color', colors{i});
end
xlabel('Time (s)');
ylabel('Joint angular velocity (degrees/s)');
title('Elbow joint angular velocities over time');
legend show;
hold off;

% Plotting knee angular velocity
figure;
hold on;
for i = 1:num_files
    if isempty(knee_angular_velocities{i})
        % Skip processing if data is empty (file was skipped)
        continue;
    end
    plot(time_all{i}(2:end), knee_angular_velocities{i}, 'DisplayName', ['File ' num2str(i +
startnumber) ' Knee velocity'], 'Color', colors{i});
end
xlabel('Time (s)');
ylabel('Joint angular velocity (degrees/s)');
title('Knee joint angular velocities over time');
legend show;
hold off;


% Plotting ankle angular velocity
figure;
hold on;
for i = 1:num_files
    if isempty(ankle_angular_velocities{i})
        % Skip processing if data is empty (file was skipped)
        continue;
    end
    plot(time_all{i}(2:end), ankle_angular_velocities{i}, 'DisplayName', ['File ' num2str(i +
startnumber) ' Knee velocity'], 'Color', colors{i});
end
xlabel('Time (s)');
ylabel('Joint angular velocity (degrees/s)');
title('Ankle joint angular velocity over time');
legend show;
hold off;
```

```
%% Creating a function to calculate the angle of a joint by spanning 2 vectors from the joint to the nearest other joint

function angle = calculate_angle(x1, y1, x2, y2, x3, y3)
   % calculate the vectors
   v1 = [x1 - x2, y1 - y2];
   v2 = [x3 - x2, y3 - y2];

   % calculate the angles in radians
   cosTheta = dot(v1, v2) / (norm(v1) * norm(v2));
   angle = acosd(cosTheta); % Convert to degrees
end
```