Master Thesis

The influence of skating velocity on the short track relay exchange

Using Inertial measurement units

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Abstract

The relay in short track skating is a team effort with the possibility to regain strength during the race by performing an exchange with a team member. Couples can gain time and conserve kinetic energy with a well performed exchange. However, the exchange is a difficult operation. With few studies done to find out what makes a good relay exchange, the exchange is rather based on experience than on knowledge. Former studies investigated the kinetic energy efficiency and the straight time with and without exchanging to find positive and negative influencing factors.
To study the influence of skating velocity on relay efficiency, both the Dutch National short track team and RTC North participated in a test setup. Two inertial measurement units, worn in a waist belt during the relay training exercises, provided acceleration data during the relay exchange. The acceleration data from both the pushed and pushing skater were studied to find out what the influence of the skating velocity is on the performance of the exchange. Horizontal accelerations of the pushing and pushed skater were transferred into total horizontal forces with the difference between these total horizontal forces (ΔF) deemed as an efficiency value for the relay push.
A weak positive correlation is found between: ΔF and the skating velocity of the pushed skater and the deceleration of the pushing skater and the skating velocity of the pushed skater. Camera images revealed the accelerations of the pushed skater to be a combination of the exchange push and the first stride, with no distinction visible between them in the corresponding acceleration data. The influence of the first stride is unknown, making the acceleration data difficult to interpret.

1 Introduction

1.1 Background

The relay is a team effort within the short track skating sport. During the race, one skater of every team is racing in a pack race. The racing skaters can be relieved by performing a relay exchange with one of their team members. Exchanging couples have to tag each other during the exchange. They are allowed to perform a push to give the incoming team member a head start into the race to conserve kinetic energy. The exchange happens every one and a half or two laps, giving the other team members a moment to regain strength in the inner part of the rink.
Within the short track sport, the goal of the race is not the fastest finishing time but the order of finishing skaters. This results in a competition in which the racing skaters challenge each other to raise the velocity and to take over the leading place in the pack. This makes the game a combination of tactics and endurance. The exchange adds a new layer of tactics and techniques. The teams can gain or lose time depending on their exchange efficiency.
In short track, the relay differs from other relay sports with the possibility to get physical contact during the relay exchange. In contrast with swimming or athletics, where the passing of the baton or the touching of the swimming pool wall has the function of cancelling out kinetic energy transfer. One of the only exceptions is the track cycling relay, in which similar relay exchanges occur. A pulling motion of the former racing cyclist accelerates the new cyclist into the race.

Due to relatively little available literature (subsection 1.2), the short track exchange is a rather unpredictable feature of the relay. Few studies have been done to find out what is and what is not beneficial for the relay. This makes the short track relay based rather on experience than on knowledge. Which couple will perform a good exchange is hard to predict. With the upcoming mixed gender relay, with a set number of laps per exchange and a fixed order of male/female exchanges, the need for more insight in the physics of the relay exchange is even higher.

1.2 Short track relay studies

Only three studies are available regarding the short track relay competition: Riewald et al. [1997], Osborough & Henderson [2009] and Hext et al. [2017]. These studies have focused primarily on the exchanging phase of the relay. In this section the research goals, methods and results of these three studies will be analysed and compared.

The study of Riewald et al. [1997] focuses on the timing and the energetics of the relay, by recording and digitizing a mid-pelvic point motion of the exchanging skaters. This resulted in the velocity, 3d position and kinetic energy of each participant. Also a subjective ranking was provided by the coach for every relay (bad, average or good). Finally, the kinetic energy efficiency of the relay exchanges are expressed in the total kinetic energy gained and the total kinetic energy lost through the exchange (Equation 1):

$$\text{Relay efficiency} = \frac{\sum E_{kin_{gained}}}{\sum E_{kin_{lost}}} \qquad (1)$$

In which the kinetic energy is computed with the skater's masses and velocities.

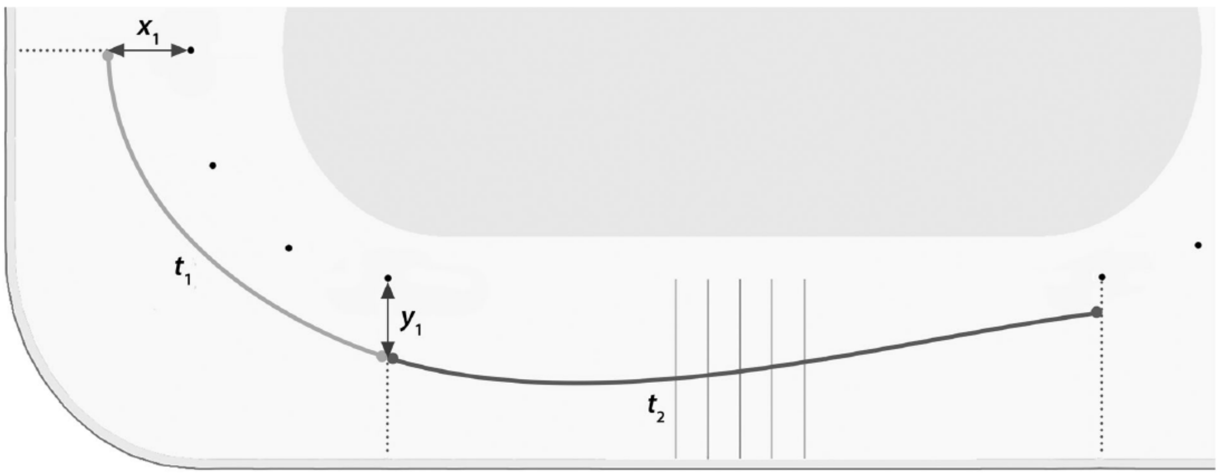
Riewald et al. [1997] points out two major independent factors in the relay exchange efficiency:

- The energy exchanged during the moments of contact.
- Most energy seems to be lost before the moment of contact. This did correlate with the ranking of the coach.

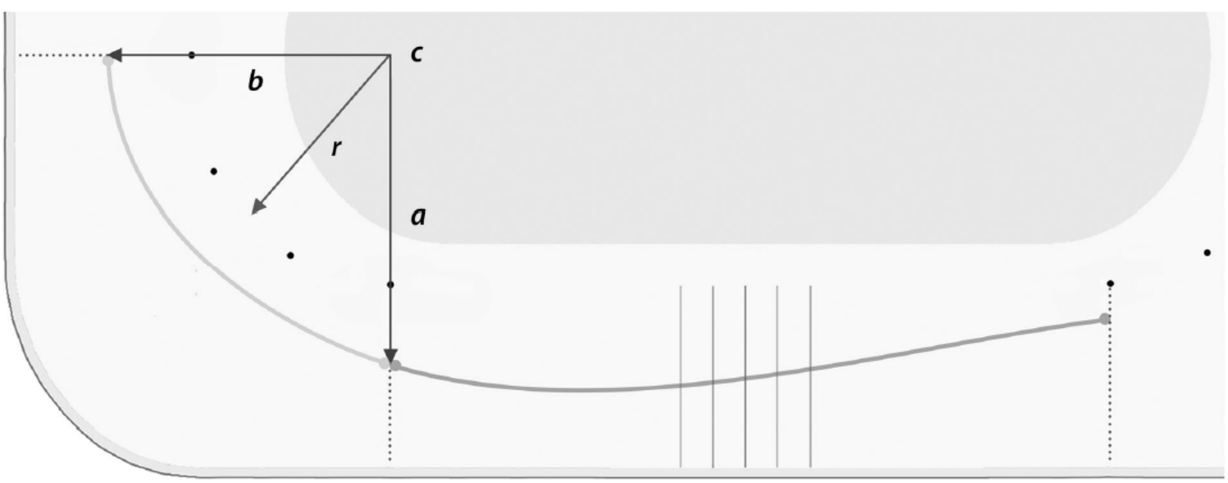
An overall efficiency of the total relay exchange was determined at $50.5 \pm 9\%$, being a combination of the independent losses prior to the exchange and energy transfer during the exchange. The energy transfer during the exchange matched the ranking of the coach, the contact loss before the exchange did not (Riewald et al. [1997]).

Osborough & Henderson [2009] focuses primarily on the position of the exchange on the straight. The research compared the location of the relay exchange on the straight, with the overall skating velocity during the exchange. The straight was divided into three zones where the relay exchange could be executed (early, mid or late on the straight). For every relay, skaters were instructed to perform the exchange in one of the three zones. Similar to Riewald et al. [1997], three cameras recorded the relays to study the location and movement of the hip joint centre to estimate corresponding skating velocities. The results of this study did not show a significant difference in the mean skating velocity between the three zones. However, starting the exchange in the middle zone of the straight resulted in the fastest and more consistent skating velocity compared to the other two zones.
The most recent research of the short track relay is from Hext et al. [2017]. This research compares the exchanging straight times and the non-exchanging straight times with various skating velocities. With a straight time being the time to pass a single straight length of the lap.

For this research a single static camera setup was used to collect competition footage of the whole ice rink. Calibration was done via six corner marking blocks in combination with a two-dimensional direct linear transformation. This provides a calibration of a 2D plane of the rink surface, making it possible to estimate positions and travelled distances over the track. The rink was divided into two halve laps, with each three sections: straight, corner entry and corner exit. Every passing position into a new section was manually digitised and the absolute time spend within the section was stored.
The reliability of this one camera was assessed (Hext et al. [2016]), in which the straight time estimations of one camera were validated with two synchronised cameras perpendicular to the start and the end of the straight.
With a data-set of exit/entry locations per section and the absolute time spend in every section, the data was used to estimate travelled paths through the corner sections and corresponding velocities. This was accomplished by estimating the distances y_1



(a) Estimated values y_1 and x_1 from camera images



(b) the radii a and b of the elliptical path through the corners, a = r + x_1 and b = r + y_1

Figure 1.1: Two elliptical radii a and b to estimate the path through the quarter corner

and x_1 (Figure 1.1). With the corner radius known, the two elliptical radii a and b could be calculated. With Equation 2, the total circumference of the ellipse was calculated. Taking $\frac{1}{4}$th of this value resulted in the paths through every half corner. Together with the absolute travel time, every half corner velocity was estimated by dividing travelled distances by the absolute travel times.

$$\pi(a+b)\left[1+\frac{3\left(\frac{a-b}{a+b}\right)^2}{10+\sqrt{4-3\left(\frac{a-b}{a+b}\right)^2}}\right] \quad (2)$$

The study analysed the data in increasing velocity ranges, and found a correlation between the influence of the relay exchange on the straight time and the corner exit speed. With slower corner exit speeds, the relay exchange had a positive effect, meaning the straight time with the relay exchange was faster compared to the straight time without the relay. However, with increasing corner exit speeds, this positive effect decreased and even became a negative effect (slower straight times with the exchange versus without the exchange). Hext et al. [2017] discussed three possible factors for this negative influence of the velocity on the exchange:

- Matching the corner speed of your teammate may be more difficult with higher corner speeds. The incoming skater has to match the velocity of the teammate in a smaller corner radius, causing a higher corner force to overcome than the normal corner radius. A relation with the coefficient of restitution (Appendix 2: Collision theory) was made. By keeping all the variables constant, except increasing the initial velocity of the incoming skater V_{2i}, the difference in relative final velocity and therefore the resulting V_{2f}, will become lower.
- With a relative constant force applied by the pushing skater, the contribution of the push decreases with higher velocities, due to the higher momentum of the pushed skater prior to contact.
- With higher velocities, the exchange will take more distance on the straight, causing the pushed skater to have less distance on the straight left to accelerate on before entering the new corner.

An overall recommendation of Hext et al. [2017] is to vary the number of laps per relay exchange depending on the skating speed, making it a more tactical aspect of the race. Normally the race starts at lower speeds, which makes a higher exchanging frequency more suitable to conserve as much energy as possible. During the last sprinting phase of the race, in which the exchange is assumed to have the highest negative effect on the straight time, a lower exchanging frequency should be adapted.

1.3 Problem analysis

With only Hext et al. [2017] recommending an improvement of a tactical aspect (to vary the frequency of the relay depending on the skating velocity), the short track skating is missing a clear vision how to improve the relay exchange.

The idea of Hext et al. [2017] of skipping an exchange or prolonging the last laps before exchanging was not well received by the coach and trainers of the Dutch National Team (conducted by an interview). They could not imagine a longer lap during the last phase of the race, in which endurance, fatigue and higher effort for the sprinting velocities plays a more crucial role in winning the race. Additionally, the rules prohibit exchanges during the last two laps of the race(ISU.org [2018]). Also the number of laps per exchange is set during upcoming mix gender competition with new rules (ISU.org [2019]). Both the dislike of skipping the last exchanges for a tactical advantage and the upcoming mixed gender relays, makes further investigation on the possible negative influence of the increasing skating velocity on the relay exchange necessary.

To study this possible negative effect of the increasing velocity, the method used to distinguish between efficient and inefficient relays should be improved. All three studies use kinematic estimations from camera images to derive a representation of an efficiency indicator of the exchange. They do not take into account independent factors, like the strides made on the straight. This influences the estimated velocity over a segment or the straight times in case of Hext et al. [2017]. In order to find the direct influence of the exchange on the lap times of the race, and especially the push during the exchange, the difference between the acceleration of the pushed skater and the decelerations of the pushing skater, caused by the push should be examined. In this way it can be investigated whether the exchange efficiency is really influenced by the skating velocity.

1.4 Research goal

The aim of this study is to improve insight on the influence of the skating velocity on the short track relay exchange efficiency.

2 Method

2.1 Relay efficiency

During the push of the exchange, both skaters experience a force on the horizontal plane. The pushed skater in the forward direction (Equation 3) and the pushing skater in a backwards direction (Equation 4). These summation of forces are a combination of the pushing force, the friction on the ice, the draft on the skaters and losses caused by inefficiencies during the exchange.

(Equation 3, Equation 4).

$$\sum \overrightarrow{F}_{\text{pushed skater}} = m \cdot \overrightarrow{a}_{\text{pushed skater}} \tag{3}$$

$$\sum \overleftarrow{F}_{\text{pushing skater}} = m \cdot \overleftarrow{a}_{\text{pushing skater}} \tag{4}$$

These two forces are non-equal (Equation 5). The absolute value of the difference between the two are deemed to resemble the efficiency of the push, caused by the amount of losses during the exchange.

$$\sum \overrightarrow{F}_{\text{pushed skater}} \neq \sum \overleftarrow{F}_{\text{pushing skater}} \tag{5}$$

$$\Delta F = \left| \sum \overrightarrow{F}_{\text{pushed skater}} - \sum \overleftarrow{F}_{\text{pushing skater}} \right| \tag{6}$$

$$\Delta F = \sum F_{\text{losses}} \tag{7}$$

A change in the relay efficiency will be studied using forward acceleration data of the two skaters during the push of the exchange. To compare the acceleration data between different couples, the accelerations caused by the push of the exchange will be transferred to total horizontal forces by multiplying the accelerations with the skater's masses.
With both skaters at almost the same velocity, the frictions of the ice and the draft on the two skater will be comparable. With the skaters synchronising their velocity before the exchange, the relative velocity between them should stay close to zero. The difference between the two horizontal forces should stay similar with both lower and higher velocities. In case of a decrease of efficiency with higher velocities, the difference between the deceleration and accelerations should become higher.

2.2 Data collection

From December 2019 to March 2020, a total of 24 training relay sessions are used to perform the measurements. All data was collected in an indoor ice rink in Thialf, Heerenveen. Both the Dutch national team (20 sessions) and the youth talents team (*RTC Noord*) (12 sessions) participated after signing a written informed consent, resulting in a total of 196 successful relay exchanges. During training sessions, skating couples were selected by input of a trainer/coach of the team, based on the position of their exchange (finish line or opposite straight). Measurements with incomplete or corrupted data were removed from the data set.

2.3 Measuring setup

Acceleration data from both the pushing and pushed skater is collected. This is combined with an estimation of the skating velocity during every exchange. Acceleration data is divided over two groups, low and high velocity relay exchanges. These velocity groups are based on the mean velocity of all measured relay exchanges. An increase in horizontal force differences (Equation 6) will represent a less efficient relay exchange (subsection 2.1). If this occurs more with higher velocities, the negative relation of increasing velocity on the relay efficiency could be confirmed.

Only one straight of the lap was considered for this research. Both the straight in which the exchange is performed and the number of laps per skater before exchanging can vary. In case of an odd number of laps per exchange, only halve of the exchanges occurred in front of the cameras.
All the equipment used in this study was provided by *Innovatielab Thialf*. For the measurements, three sensor systems are used to analyse the relay exchange:

- Two *inertial measurement units* (IMU). These sensors provide the forward acceleration data during every relay exchange (subsection 2.4).
- A camera in front and one behind the exchange. These two cameras provide insight regarding the travel path of the skaters through the corners (Figure 2.3). Also one handheld camera from a side view of the relay provided back up information in case of strange or abnormal data results.
- The Mylapse transponder system. A system normally used to provide lap times of the skaters. In this setup used for segment lap times (subsection 2.5) and identification of the relay exchanges (subsection 2.6).

2.4 Acceleration data

The acceleration data is collected with two NGIMU sensors from *Xio Technologies*. These IMU's provide data of the local acceleration and the orientation of the sensor. The global acceleration relative to the earth axes can also be measured with an internal *altitude and heading reference system* (AHRS). For this measurement, gravity free accelerations are measured with a frequency of 50Hz, to analyse the accelerations caused by the push during the exchange.

Both sensors were activated and synchronised via a WiFi signal. After this signal, the sensors logged the data to their own internal SD card. Velcro waist straps allowed the skaters to easily enable the sensors during the training. In the belt, the sensor was in a fixed orientation relative to the skater's upper body. Standing upright, the sensors Y-axes pointed upwards, the Z-axes forward and the X-axes into the rink. During skating, the skater would tilt forward causing the sensors to rotate around its x-axes, making the forward acceleration a combination of the roll angle and the local Z- and Y-axes (Figure 2.1 .

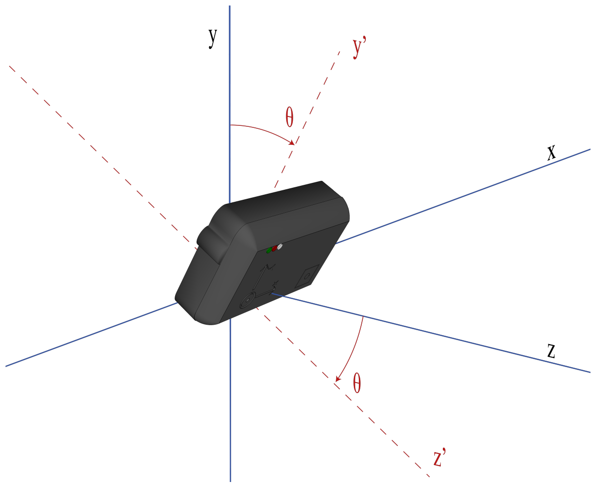


Figure 2.1: Roll angle during skating of the NGIMU sensor

2.5 Exchanging Velocity

In order to investigate the influence of velocity on the relay efficiency, a skating velocity needed to be estimated. This is achieved by a path estimation with the front and back camera in combination with a lap segment travel time of the Mylapse transponder system, resulting in the mean velocities of the skaters during the relay exchanges.

2.5.1 Mylapse: Segment lap times

In the ice rink of the Thialf ice stadium five sensors of the Mylapse system are embedded in the ice (Figure 2.2). In combination with two transponders per skater worn around the ankles, the Mylapse system is able to keep track of every sensor passing by the skaters. By measuring the difference between the start and finish sensor passings, the total lap time can be provided in an accurate manner.

Within the Mylapse system, the finish sensor is backed up with an extra sensor 10 meter before the finish line (Figure 2.2, sensor 3). This sensor is used to provide lap times for the skaters giving the push during the relay exchange, causing them to slow down drastically before finishing. With the extra sensor before the finish line, these pushing skaters can still get insight in their lap times. This extra sensor on this part of the track is used in combination with the finish sensor (sensor 4) to estimate the skating velocities during the exchange. The travel times in the corners (from 2 to 3 and from 4 to 5) are less accurate, caused by the movement of the track by re-positioning the corner cones to preserve ice quality during the training (Figure 2.3). The Mylapse system is static within the ice, causing the travel times between these sensors sets to be dependent on the position of the rink on the ice. For this reason, only the velocities between sensor 2 and 3 are used. Sensor 1 is not used for velocity estimations. However, it served a purpose with distinguishing completed laps from random sensor passings in the Mylapse data.

2.5.2 Path estimation

To achieve an accurate velocity estimation, a path estimation of segments of the half lap (from corner 1 to corner 2) is based on two assumptions:

1. The two halve corner segments are estimated like the method of Hext et al. [2017]. With the two elliptical arc radii x_1 and y_1 (Figure 1.1a), resulting in radii a and b (Figure 1.1b) and the distances calculated via Equation 2.

2. The two skaters are moving from y_{1enter} to y_{1exit} (Figure 2.3) in one straight line. This is based on the short period of the couple gliding as one before the relay push. After this push, the second skater will move to the next corner, where y_{1exit} is recorded. This assumption is not entirely accurate, because it does not take the strides of the skater after the push into account. Causing the real path between y_{enter} and the y_{exit} to be slightly longer. However, it will be useful for

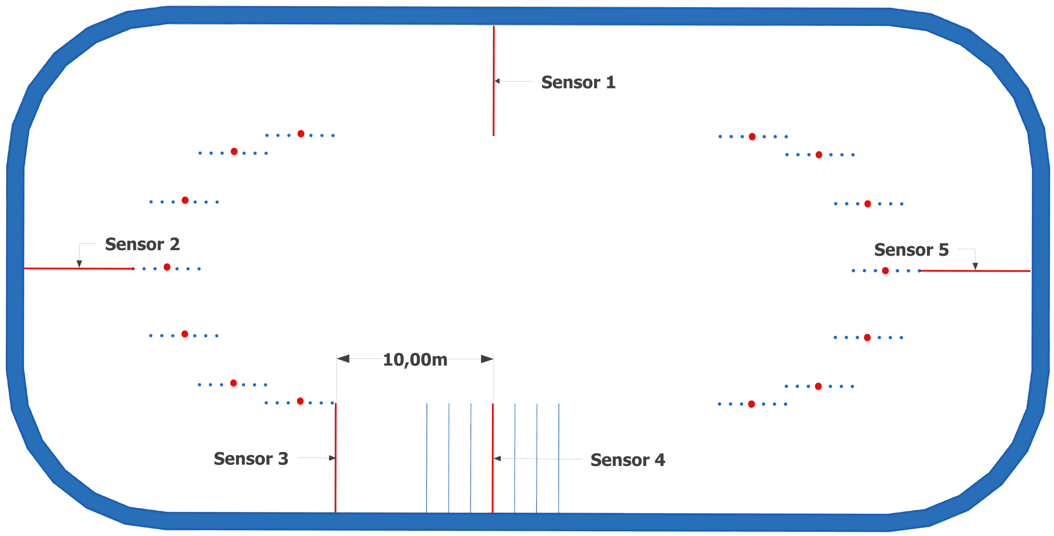


Figure 2.2: Mylapse sensors within the Thialf short track ice-rink

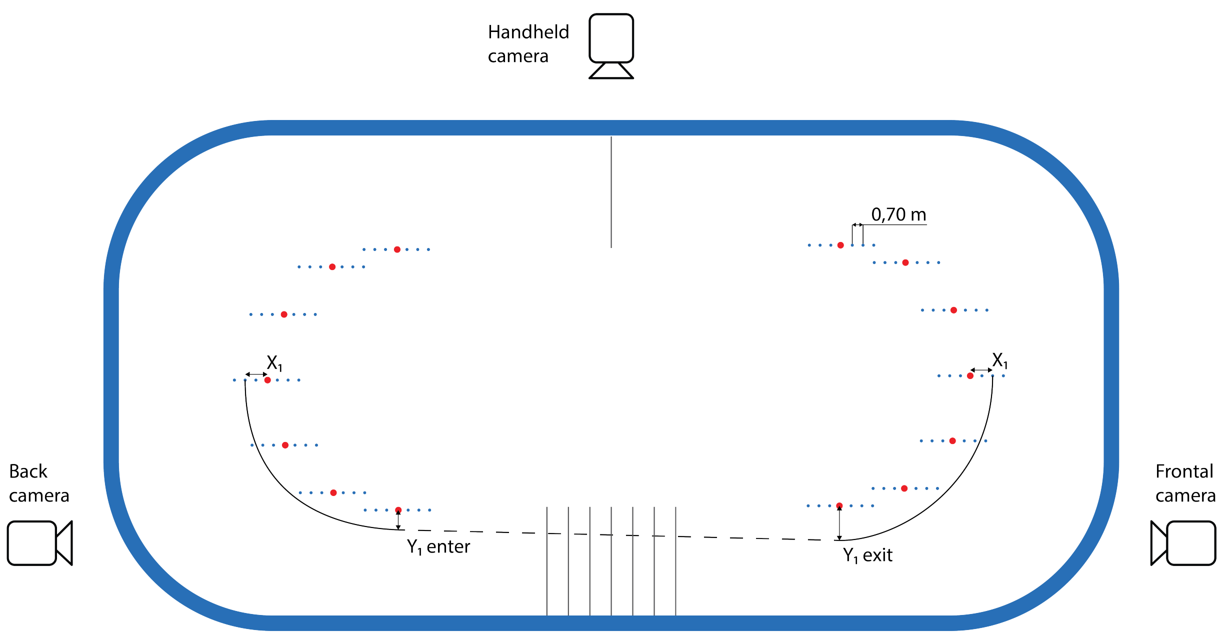


Figure 2.3: Re-positioning of 70 cm of the lap to maintain ice quality and path estimation based on camera images and two elliptical paths through the corners, connected via a straight line from y_{1enter} to y_{1exit}

differentiating between lower an higher velocity relay exchanges.

The x_1 value is estimated to be 0.3 meters, the corner radius is 8.5 meters, resulting in $a = 8.9$ meters. The y_1 values were dependent on the velocity of the skater. Therefore, it was measured for every single relay exchange with a camera. The straight entering corner was recorded with the camera at the back of the relay exchange (Figure 2.4) and the exit corner was recorded with a camera in front of the relay exchange((Figure 2.5). With these images, and the distance between the last corner cone and the opposite border, the overshoot of the corners could be measured. Resulting in two y_1 values per relay, the y_{enter} and the y_{exit} .

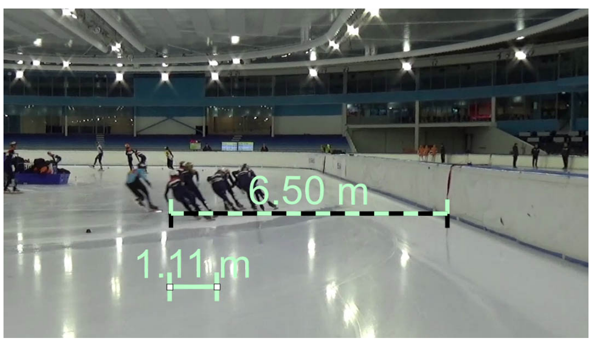


Figure 2.4: Back camera view for y_{enter}

Figure 2.5: Back camera view for y_{exit}

The cones of the corners are re-positioned 70 cm every few laps during the training to avoid deep groves in the ice and preserve good ice conditions.

In order to measure the same distance from the end of the corner cones to the rink border, a movable mark has been made. These red marking cones hang from the rink border and pinpoint the exact location of the opposite of the last corner cone. A line is digitally drawn between these two markers to find the length of overshoot y_{enter} and y_{exit}. The outer or right skating blade is chosen as first contact point of the skater from where the distance to the corner cone is measured. This blade was more likely to be in clear view of the camera during the passing of the digital line compared to the left skate due to the trajectory of the skaters in front of the cameras. Arguably, this causes a small measuring error when the skater is excessively leaning inward when passing the line, causing the centre of gravity of the skater to be closer to the inside of the track than estimated.

2.6 Data synchronisation

The Mylapse had the secondary function of pinpointing the moments of the relay. Different sections and exercises were identified based on the moment of passing the finish line of the two skater.

With the possible moments of a relay exchange known, the two acceleration data sets could be synchronised to this time vector to find all the moments on the straight segment of the lap with a relay exchange. The sensors had a drift error, so fine-tuning both data was done manually using a developed Matlab *Graphical User Interface* (GUI) app. This was done by synchronising the high acceleration values during the corners with the Mylapse corner passings. Corners were chosen instead of other Mylapse passings due to its independence on the re-positioning of the rink during the training. With all the synchronised data, the peaks could be selected during the push.

3 Data analyses

Patterns were recognised using the video images for the pushing skater, the pushed skater and a free skating halve lap (skating the straight without relay exchange). In Appendix *Acceleration Patterns* a more in dept analyses of the three situations is described.

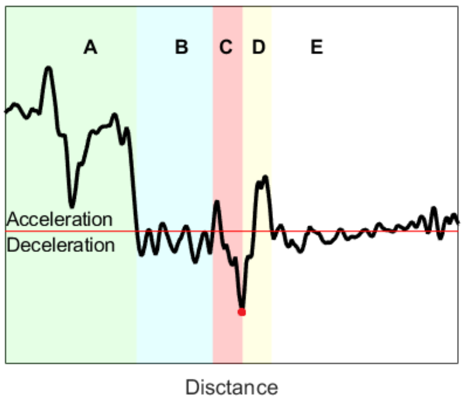


Figure 3.1: Acceleration pattern of the pushing skater. A= entering corner, B = initial contact, C = push, D = push recovery and E = rest after exchange
Red dot is chosen value of deceleration

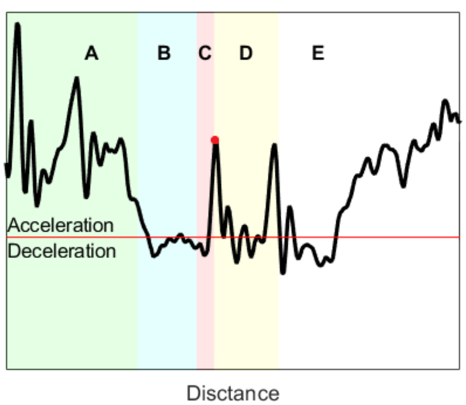


Figure 3.2: Acceleration pattern of the pushed skater. A= entering corner, B = initial contact, C = push, D = strides before next corner and E = exit corner
Red dot is chosen value of acceleration

For the pushing skater a typical deceleration is noticed during the push (zone C, Figure 3.1), followed by a segment with zero acceleration, indicating the resting period of the pusher after the exchange (zone E, Figure 3.1).

For the pushed skater, the push was less recognizable. The peak of the push (zone C, Figure 3.2) was identified as the first peak after the so called 'initial contact zone (zone B, Figure 3.2). However, these peaks caused by the exchange did not behave differently from normal stride peaks after the exchange. Also the difference between the push accelerations and the first stride were not distinguishable.
The free skating data and camera images confirmed that the strides over the straight were easily identified (Figure 3.3).

For the deceleration value of the pushing skater, the minimum value in zone C was chosen of Figure 3.1. The acceleration for the pushed skater is the peak value in zone C of Figure 3.2. Both points are marked with a red dot in Figure 3.1 and Figure 3.2. These two values were saved with the corresponding skating velocities of the two skater in the data set.

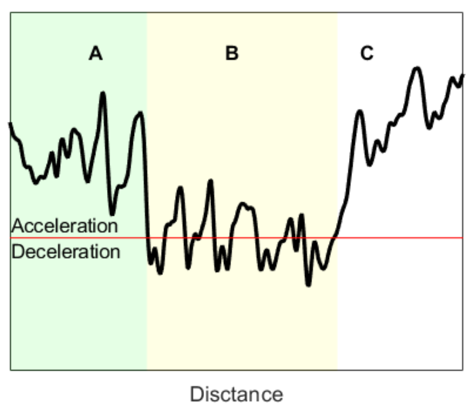


Figure 3.3: Acceleration pattern of a free skating straight.
A= entering corner,
B = strides before next corner and
C = exit corner

4 Results

4.1 All data

The relay exchange efficiency is expressed in terms of the difference of the horizontal forces (Equation 7). An increase of this force difference represents a more inefficient relay exchange. From the measurements of all skaters a small decrease in efficiency can be seen with higher skating velocities of the pushed skater. This is shown in the scatter of the ΔF with the *Velocity Pushed* (Figure 4.2).

	n	Velocities [m/s]			ΔForce [N[		
		Min	Max	Mean	Min	Max	Mean
All	178	30,6	45,8	36,9	0,8	971,2	195,2
NL	101	30,8	45,8	37,1	7,8	971,2	203,4
RTC	77	30,6	42,7	36,7	0,8	669,0	184,6

Figure 4.1: Overview of the results from the data set

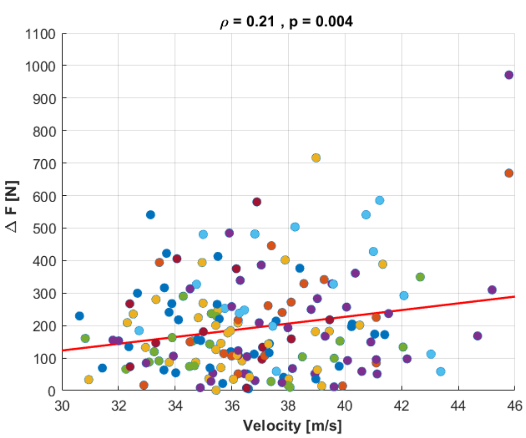


Figure 4.2: Scatter of the force difference and the velocity of the pushed skater of the 17 participating couples. Every couple has an unique dot color

The data does show a significant but weak correlation between velocity and efficiency of relay exchanges (p = 0.013 and ρ = 0.25). This suggests that velocity magnitude is weak positive correlated to the force difference between the skaters. Although the data from the group does show a correlation between the velocity and the ΔF, the individual couples are highly scattered over the data set, show in Figure 4.2 with the different colored dots.

4.2 Difference between the teams

Regarding the Dutch National team and the RTC Noord team separately provides insight in a difference in experience between the two groups. Figure 4.3 and Figure 4.4 are used to observe the two teams separately. These graphs have also the acceleration and deceleration included, to see what causes the value of ΔF.

- First of all, although the mean velocities between the teams are similar (Figure 4.1), but the maximum velocities of RTC Noord are lower compared to the Dutch National team (Figure 4.3 and Figure 4.4). This was expected with RTC Noord being the less experienced group. The magnitudes of the accelerations, decelerations and ΔF are not behaving differently.

- Regarding the correlation of the ΔF scatters for both groups, the Dutch National team shows a similar poor correlation as the total group. With a $\rho = 0.25$ and a p-value of 0.013. However, the RTC group does not show a significant correlation between the velocity of the pushed skater and the ΔF, with a p-value of 0.18. The maximum velocities of this group are lower, possibly causing a less correlated data set. Nevertheless the ΔF values are also not increasing with the velocity, but rather scattered more evenly.

- For both the Dutch National team and RTC Noord, the deceleration scatter shows a stronger correlation with increasing velocity compared to the accelerations.

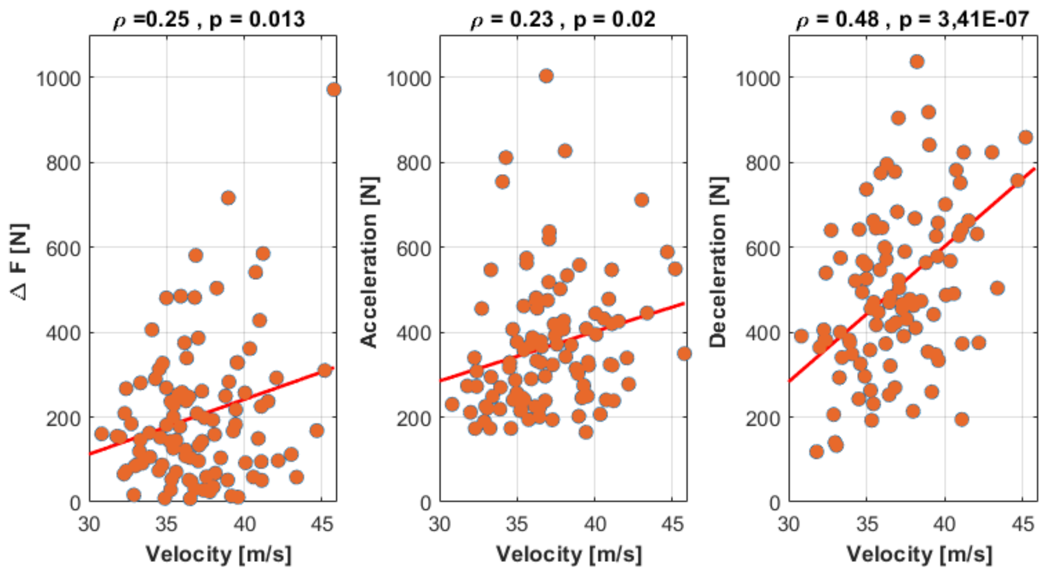


Figure 4.3: Data from the Dutch National team. Scatter plots of the force difference, the accelerations and the decelerations

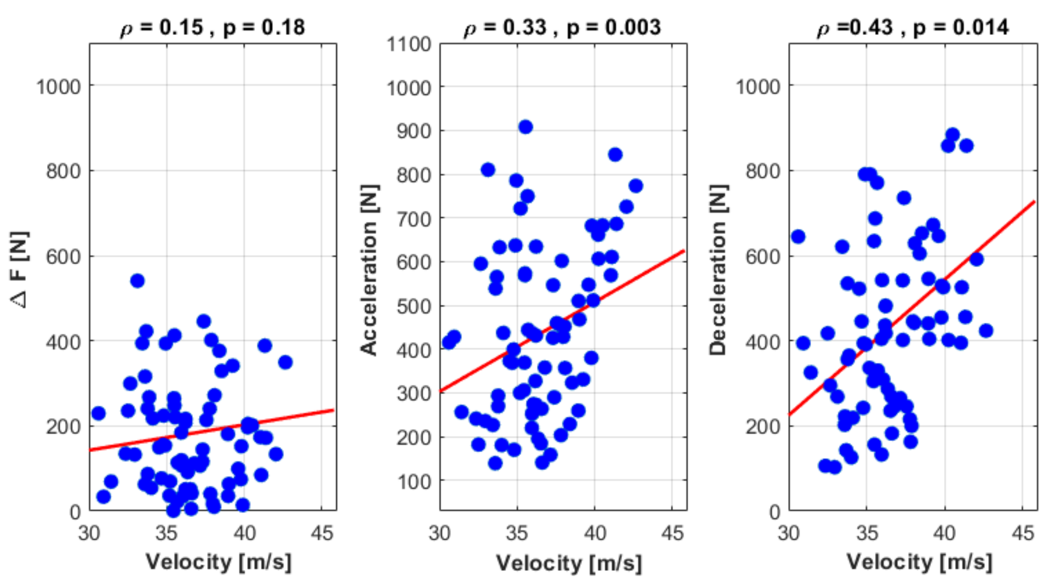


Figure 4.4: Data from RTC Noord. Scatter plots of the force difference, the accelerations and the decelerations

5 Discussion

5.1 Data interpretation

With only a poor positive correlation between the velocity and the difference between the horizontal forces of the two skaters, it is hard to determine if the relay really becomes more inefficient with higher skating velocities.

Figure 4.3 and Figure 4.4 show different behaviour between the two teams, with the Dutch National team having a more correlated data set compared to the total data correlation of Figure 4.2. On the contrary, the correlation between the skating velocity and the ΔF of the RTC Noord team was statistical non-significant. The skating velocities of this group are slightly lower, causing the influence of higher velocities to possibly be less. However the corresponding ΔF values are more random scattered.
For both teams, the deceleration is better correlated with the velocity compared to the acceleration. Implicating a different behaviour of the pushing skater during higher velocities. The difference between the acceleration and the deceleration is obscure. A more in-dept analyses with the camera footage was needed to better understand the data.

5.2 First acceleration peak

Counting the acceleration peaks of the pushed skater and the strides on camera footage shows that the peak assumed to originate from the push of the relay exchange is also caused by the first stride of the pushed skater. The IMU sensor could not distinguish the accelerations of the push and this stride. This first stride could potentially be less powerful than a normal stride during free skating. However, with the push combined, it often had a similar acceleration magnitude as the following strides on the straight.

5.3 Training situation

This setup did not account for the different goals of the training. Some trainings only consisted of one short relay exercise and others included multiple 30 minute relay sessions. Regarding the difference between the short and long duration relay exercises, the influence of fatigue was not taken into account. The 30 minute relay exercises excessively exhausted the skaters and had a higher focus on energy conservation compared to the short duration exercises. A more uniform relay exercise should improve the reliability of the velocity influence.
The number of skaters on the ice or within the racing pack varied as well. The number of skaters in the racing pack will highly influence the effort it takes to re-position in the new racing group direct after the exchange. With the measured first acceleration peak of the pushed skater possibly originating from a combination of the push and the first stride, the magnitude of the peak will behave different in a more crowded situation, where complete accelerations are more limited by surrounding skaters.

6 Recommendations

6.1 IMU positioning

In this test setup, both sensors attached to the body of the skaters using a waist belt to get the sensor in a nearly fixed position closest to the centre of mass of the skaters. The data from this sensor setup was less clear than expected. It is recommended to investigate the influence of different locations of the IMU sensors on the skaters body. The sensor mounted to the skate has showed in other studies van der Kruk et al. [2019] to be a sufficient method of differentiating between the strides and gliding phases. A combination of one sensor in the waist belt and one sensor mounted to one of the skates could probably help to improve the

distinguishing of the accelerations of the push from the stride accelerations.
For the pushing skater, this re-positioning of the sensor is less necessary because this skater will continue gliding with almost the same posture after the push.

6.2 Separate relay exchanges

Separate relay exchanges can be investigated, with the pushed skater interrupting the race directly after the push and gliding with parallel blades similar to the pushing skater. The result of this exchange would merely be the deceleration and acceleration just caused by the push itself. Both acceleration graphs would return to a horizontal line nearly zero accelerations after their peak of the push acceleration. This could investigate the influence of the push on the accelerations and find differences in efficiency between relay couples.
By varying techniques, skating couples, moments of the relay or skating velocities, more possible influences on the relay efficiency can be studied. However, it would take many trials with different couples to achieve a data set with enough samples to draw conclusions. In practice, such research methods cannot be combined with a normal relay training session, making these measurements more demanding than the current measurements. Also other influences on the relay exchange, like the positions of other racing couples in the group or pacing of the racing pack, are not included in this setup.

6.3 Adding a sensor

Finally, the relay efficiency research could be continued with an extra sensor in the measurement. This could be:

- GPS - IMU extension
- Force plates

The GPS is a common extension of the IMU system and provides location and velocity data with the data of the IMU. This could greatly improve this test setup, making the measurements less labour elaborate and more precise. Instead of estimating a mean skating velocity over a lap segment, direct velocity data could be combined with the acceleration data. This could help to identify where the skaters are losing and gaining their velocity. However, GPS-systems have to be tested for indoor use, signal distortions from the ice rink are possible.

The force plates could measure the direct force magnitude of the push during the exchange. This could be useful as a direct representation of the force put into the push. The combination of the acceleration data and the force plate data of the pushed skater could determine a horizontal force efficiency. However, the influence of the stride is again influencing the acceleration data.
Considering safety concerns with sensors on the back of the skaters, a set of gloves for the pushing skater would be a good option to allow the users to measure the force on the hands during the push itself.

7 Conclusion

This research studies the relation between skating velocities and the efficiency of the relay exchanges. A weak positive correlation was found with the skating velocity and the $\Delta Force$, implying a possible influence of the skating velocity on the efficiency of the relay exchange. However, regarding both the Dutch national team and the RTC youth team as separate populations showed different results. With the national team having similar correlations as the complete data set and the RTC team having a non-significant correlation between $\Delta Force$ and the skating velocity.
The $\Delta Force$ variable appeared to be not only caused by inefficiencies of the push, but rather a combination of both the sum of the losses ($\sum F_{\text{losses}}$) and the stride force of the first stride.

More research is needed to better understand the relation. If the F_{stride} could be distinguished from the $\Delta Force$ variable, a more distinct assessment of the dependency of skating velocity on the efficiency of the relay exchange could be found.

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Appendix A: Rules of the relay exchange

The following rules are from the ISU regulations (ISU.org [2018]) from 2018. This is updated in 2019 for the mixed gender relay competition(ISU.org [2019].

- Teams compete with one racing team member. The other members should be out of the way of the track and may only be on the inside of the rink.
- Relaying can be performed by touching the racing team member. Although every skater has to skate at least one lap per before exchanging.
- In the situation of a fallen skater, team member have to perform an exchange by tagging the fallen skater.
- An exchange may be performed any time during the race except the last two laps. This will be signaled by the start of the last three laps with a sound signal. Only with a fall, an exchange may be performed.
- Relay exchanges have to executed without changing lane. A straight forward path has to be taken.

With the mixed gender relay a few extra rules are in place, updated in 2019 from Communication No. 2275:

- The teams consist of minimal four and maximal eight skaters, with equal amount of male and female team members.
- The racing distance is 2000m (18 laps).
- The exchanges follow a fixed schedule:
  - First 4x2.5 laps in the order female-female-male-male
  - Followed by 4x2 laps in the order female-female-male-male
- Skater of the same gender can change their racing order.
- In case of a fall in the last two laps, any team member can take the relay.

Appendix B: Collision theory

To get a better insight in the possible influential factors of the relay exchange of short track, a better knowledge of the mechanical background is needed. During the exchange, the incoming skater tries to achieve a highest possible end velocity by receiving a push from his teammate. This alignment of the two skaters with their own velocities, and the transfer of energy and momentum that follows can be regarded as a collision model of two masses with their own initial and final velocities. In this chapter, the basic principles of a collision and the application within the relay exchange will be investigated to achieve a better understanding of the mechanics during the exchange. First the difference between the elastic and the inelastic collision will be discussed. Thereafter, the coefficient of restitution, a 1d model and finally a 2d model will be handled. In the following sub-chapters, collisions between two rigid bodies will be disgusted. No increase of internal energy or splitting of masses into multiple particles will be regarded.

Momentum and energy transfer in collisions

A collision is defined as a brief intense interaction of two or more masses. Through any collision linear momentum is conserved Wolfson [2007]. Momentum is defined as mass*velocity. From the equation of motion this can be rewritten as:

$$\mathbf{F} = \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(m\frac{\mathrm{d}\mathbf{x}}{\mathrm{d}t}\right) \tag{8}$$

$$\frac{dp}{dt} = 0 \tag{9}$$

$$\mathbf{p} = m\mathbf{v} = \text{ constant} \tag{10}$$

This means that the momentum through any collision of two masses can be defined as (McComb [1999]:

$$m_1 v_{1f} + m_2 v_{2f} = m_1 v_{1i} + m_2 v_{2i} \tag{11}$$

However, the conservation of kinetic energy does not have to be conserved, this is depending on the type of collision.

Elastic collisions

$$E_{kin_i} = E_{kin_f} \tag{12}$$

A collision can be elastic or inelastic. In the elastic collision, both the total kinetic energy (Equation 12) and the total momentum (Equation 11) of all the particles in the collision is conserved. For two rigid bodies this will be:

$$\frac{1}{2}m_1 v_{1i}^2 + \frac{1}{2}m_2 v_{2i}^2 = \frac{1}{2}m_1 v_{1\mathrm{f}}^2 + \frac{1}{2}m_2 v_{2\mathrm{f}}^2 \tag{13}$$

A perfect gas is one of the best examples for this collision model, the molecules bounce around and hit each other without losing any kinetic energy or momentum. However, in macroscopic scale this is not possible because of energy losses to heat, sound or internal energy. However, assuming that some systems behave as nearly perfect collisions, some easier estimations about the behaviour of the collision can be made(Wood [2017]).

One-dimensional elastic collisions

In one dimension, the collision only results in a change in velocity (with negative velocities meaning an opposite direction).

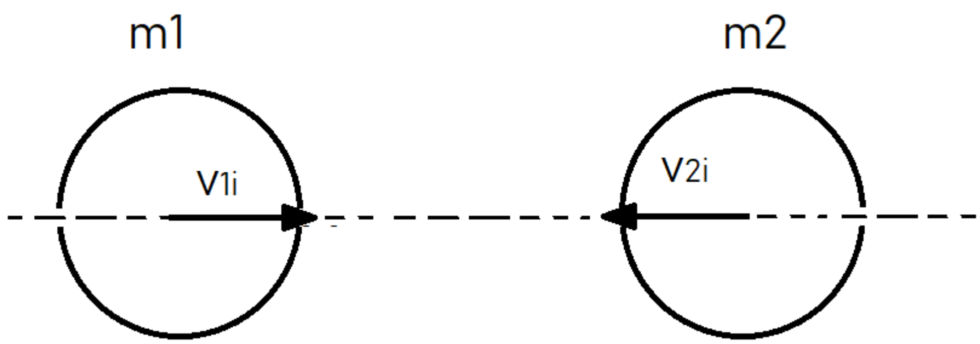

Figure 7.1: 1d collision of two masses

$$m_1\left(v_{1\mathrm{i}}-v_{1\mathrm{f}}\right)=m_2\left(v_{2\mathrm{f}}-v_{2\mathrm{i}}\right) \tag{14}$$

$$m_1\left(v_{1i}^2-v_{1f}^2\right)=m_2\left(v_{2f}^2-v_{2i}^2\right) \tag{15}$$

Starting with Equation 14 and Equation 15, Equation 15 can easily be rewritten as:

$$m_1\left(v_{1i}-v_{1f}\right)\left(v_{1i}+v_{1f}\right)=m_2\left(v_{2f}-v_{2i}\right)\left(v_{2f}+v_{2i}\right) \tag{16}$$

By dividing Equation 16 by Equation 14, the following relation between only the velocities is found:

$$v_{1i}+v_{1f}=v_{2f}+v_{2i} \tag{17}$$

and reordering gives:

$$v_{1i}-v_{2i}=v_{2f}-v_{1f} \tag{18}$$

$$\Delta v_i=-\Delta v_f \tag{19}$$

Meaning that the relative velocities stay equal, but the directions are opposite(Wolfson [2007]. Finally a mass involved relation can be found between the final velocities and the initial velocities by combining Equation 18 with Equation 11:

$$v_{1f}=\frac{m_1-m_2}{m_1+m_2}v_{1i}+\frac{2m_2}{m_1+m_2}v_{2i} \tag{20}$$

or if you apply the same calculations for the other final velocity:

$$v_{2f} = \frac{2m_1}{m_1 + m_2} v_{1i} + \frac{m_2 - m_1}{m_1 + m_2} v_{2i} \tag{21}$$

In the ideal situation with the relay push, all the kinetic energy from mass 1 is conserved and transferred to mass 2, giving the equation:

$$v_{2f} = \frac{2m_1}{m_1 + m_2} v_{1i} + \frac{m_2 - m_1}{m_1 + m_2} v_{2i} \tag{22}$$

These one dimensional calculations are very easy in case of a perfect elastic collision. Because even the most efficient relay exchange would still severely suffer from energy inefficiencies and losses, even a near elastic collision could still only serve as an indication. Also a two dimensional collision should provide more insight in the push, because the directions on the total accelerations during the collision will not be perfectly horizontal.

Two-dimensional elastic collisions

In two dimensional collisions, the impact would often be not in line with the centres of gravity of the two masses. Only a component of the forces before impact will be transferred into the collision. Also the direction of movement after impact will be different. The force and the resultant direction of movement are both dependent on the *impact parameter*, which is a measure of how much the collision differs from a head-on collision Wolfson [2007]. The basic formula's still apply here (Equation 11,Equation 12), but the velocities are swapped for vector of the velocities.

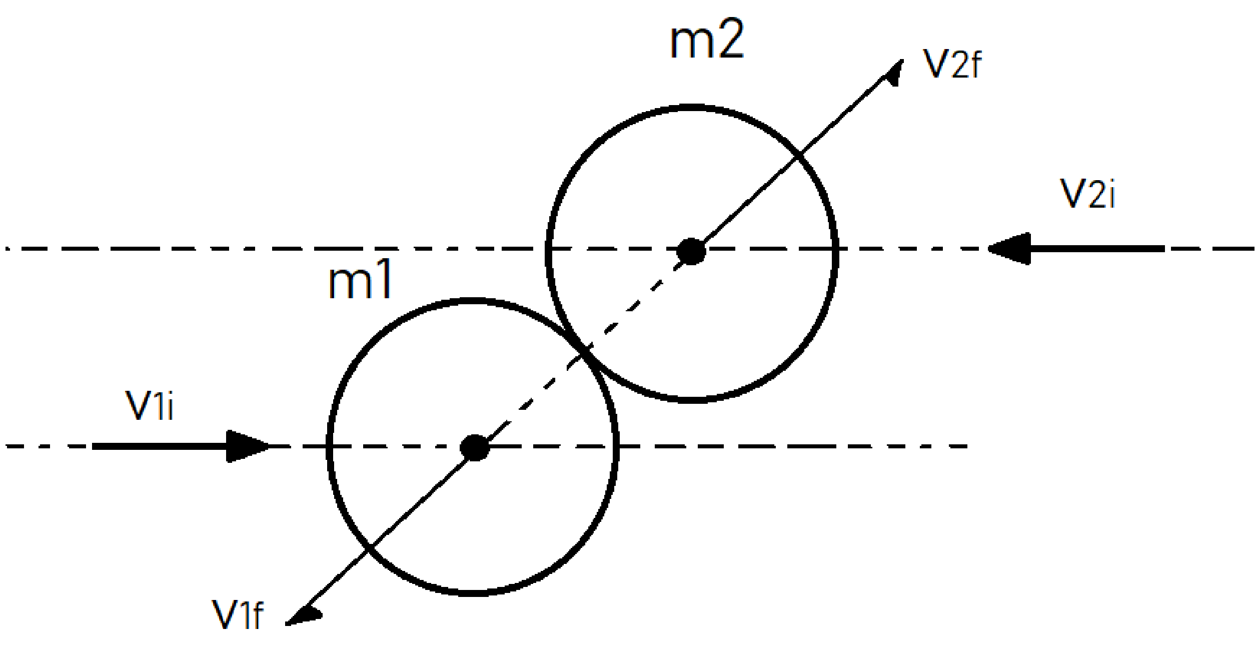

Figure 7.2: 2d collision of two masses

Inelastic collisions

Total inelastic collisions

In an inelastic collision, the total momentum is again conserved, but the kinetic energy is not. The special case would be the totally inelastic collision, where the two bodies will not separate after the collision. The resulting mass is the sum of the two former masses. This is for example possible with two magnets colliding and sticking together due to their magnetic attraction to each other. Calculations can easily be made with these collisions, being that the momentum stays within the system, but the two masses becoming one total mass (Wolfson [2007]):

$$m_1\vec{v}_{1i} + m_2\vec{v}_{2i} = (m_1 + m_2)\,\vec{v}_{\mathrm{f}} \quad \text{(totally inelastic collision)} \tag{23}$$

A direct comparison with the relay exchanging skater would be the start of the exchange, where the two skaters get in line and achieve initial contact, but the push has to happen yet (Figure 7.3). At this moment, the two skaters glide on the ice as one total mass. However, this total mass will not be completely stiff due to the impact absorbing behaviour of the arms and legs of the two bodies, causing the two skaters to not completely behave as a perfect inelastic collision.

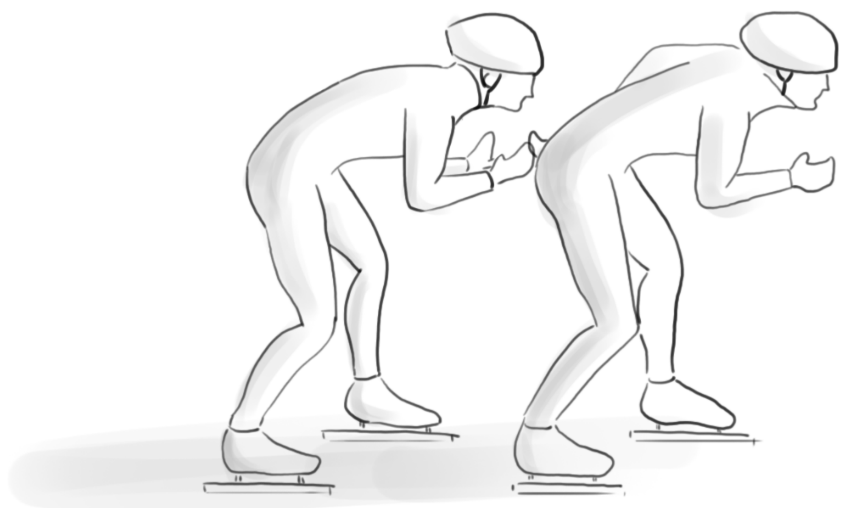

Figure 7.3: The two skaters in contact at the start of the exchange. For a short moment behaving like one mass, almost in a total inelastic collision

Near elastic collisions

Like the physics of the perfect elastic collision, the perfect inelastic collision problem is relative easily solved with the momentum balance (Equation 23).
However, just as in the example of the two short track skaters, in practice, the collisions will never be fully elastic and rarely fully inelastic. Causing the kinetic energy balance of Equation 12 to be not sufficient without including of the energy losses within the collision. Also the momentum balance of the total inelastic collision (Equation 23) is not precise due to the masses not behaving like one stiff mass. These collisions will often be called an inelastic collision, but a near inelastic collision will be more suitable. Another approach is needed to solve these near inelastic collisions that do not behave totally inelastic.

Coefficient of restitution

In case of the two bodies colliding not perfectly elastic but also not sticking together after the collision (like in case of the total inelastic collision), only the momentum balance (Equation 11) will not be sufficient to find the corresponding final velocities (one equation, two unknown variables). The kinetic energy balance (Equation 12) will also not be useful without the implementation of energy losses into the balance. To overcome this problem, a second relationship is needed for inelastic collisions.
The variable between the perfect elastic and the perfect inelastic collisions is found with the *coefficient of restitution* (Wood [2017]). This coefficient defines the relationship between relative initial velocities and final velocities (before and after collision velocities)(Ashish [n.d.]).

$$e = -\frac{V_{1f} - V_{2f}}{V_{1i} - V_{2i}} = \frac{\Delta V_f}{\Delta V_i} \tag{24}$$

For a perfect elastic collision: $e = 1$. Equation 24 becomes the elastic collision velocity balance of Equation 17. For a perfect inelastic collision: $e = 0$, the final velocities are equal ($V_{1f} = V_{2f}$) because they are the velocities of the same body m_{total} (Ashish [n.d.]). This coefficient is between 0 and 1 for non-perfect elastic or inelastic collisions and can help identifying the influence of the starting velocities of the skaters on the resulting velocities of the push.

Two-dimensional inelastic collisions

With the coefficient of restitution known via experimental data, the two dimensional collision of Figure 7.4 can be much better be understood without assuming the collision to be perfect elastic or perfect inelastic.

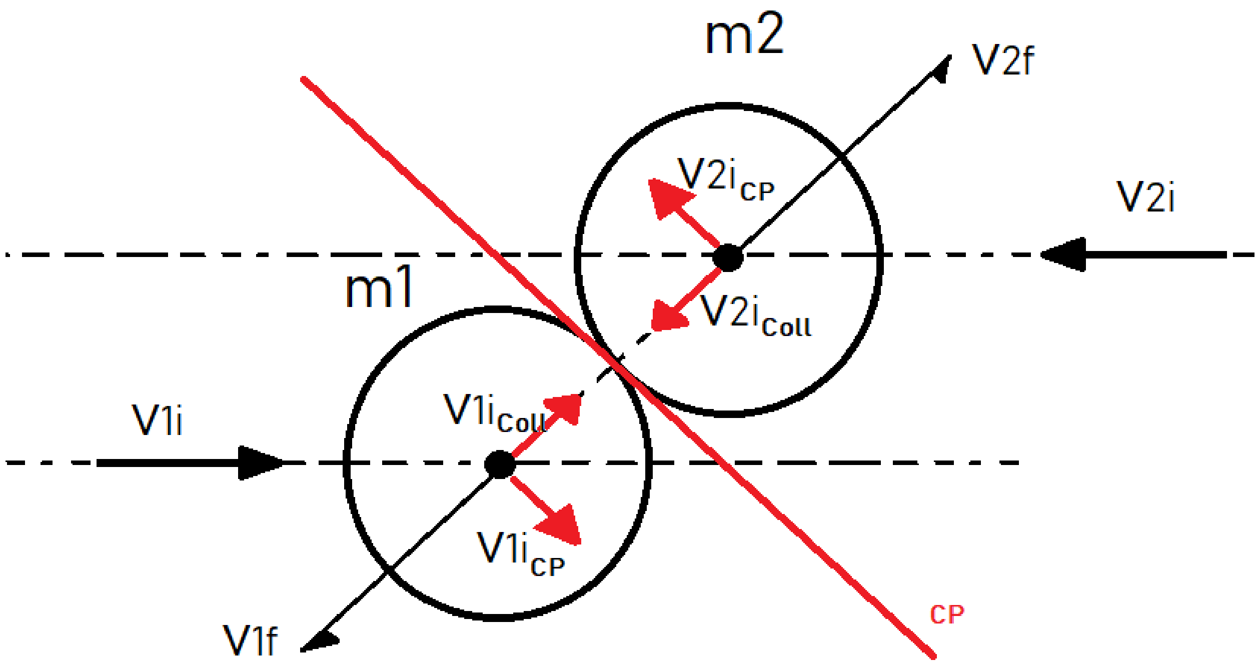

Figure 7.4: 2d collision of two masses, direction of separation depending on the impact parameter

Just like the perfect elastic example, the two initial velocities V_{i1} and V_{i2} are only partially involved in the collision with the V_{coll} components. Where the V_{coll} component is in line with the center of mass of the two masses. The other component of the initial velocity is parallel to the *contact plane* (*CP*) and has no influence on the collision. With e known, the final velocities can be calculated:

$$e = -\frac{V_{1f_{coll}} - V_{2f_{coll}}}{V_{1i_{coll}} - V_{2i_{coll}}} \tag{25}$$

The magnitude and phase of the two final velocities (v_f) can be calculated as follows:

$$|v_f| = \sqrt{v_{i_{cp}}^2 + V_{f_{coll}}^2} \tag{26}$$

$$\varphi = \tan^{-1}\left(\frac{V_{f_{coll}}}{v_{i_{cp}}}\right) \tag{27}$$

This estimation of the velocity changes caused by the collision could be very helpful to estimate real life problems, where both the perfect elastic/inelastic estimation and the 1d collision are not sufficient enough.
For the short track exchange situation this approach is also more suitable to investigate the relay exchange. Taking the angle of the resulting velocity in account, the efficiency of the push can be studied and perhaps improved, with the assumption being that the best energy transfer happens in the horizontal transfer, to accelerate the pushed skater forwards instead of downwards.

Appendix C: Acceleration patterns

From the data synchronisation part, the straights and corners were already detected. For a more precise pattern recognition, video images from the three cameras were used (front, back and side camera) to understand the data during the exchange.

Free skating acceleration data

First of all, the accelerations of a half lap without exchange is analysed, called a free skating straight.

- The first part of every acceleration data is the entering corner (green). A higher peak is area caused by the g-forces through the corners. The end of the corner can differ, depending on the last stride within the corner. Some skaters tend to exit the corner with a longer stride, continuing the curve of the corner into the straight.
- During the straight multiple strides are easily identified with the peaks occurring. Often, the magnitude of these peaks are not very divergent.

This acceleration profile can differ in peak magnitude and duration, depending on the skating velocity. Higher velocities result in smaller graphs with higher peaks in the corner areas. The stride peaks are not necessarily higher with higher velocities. These seem to be more dependent on the intensity of the exercise.

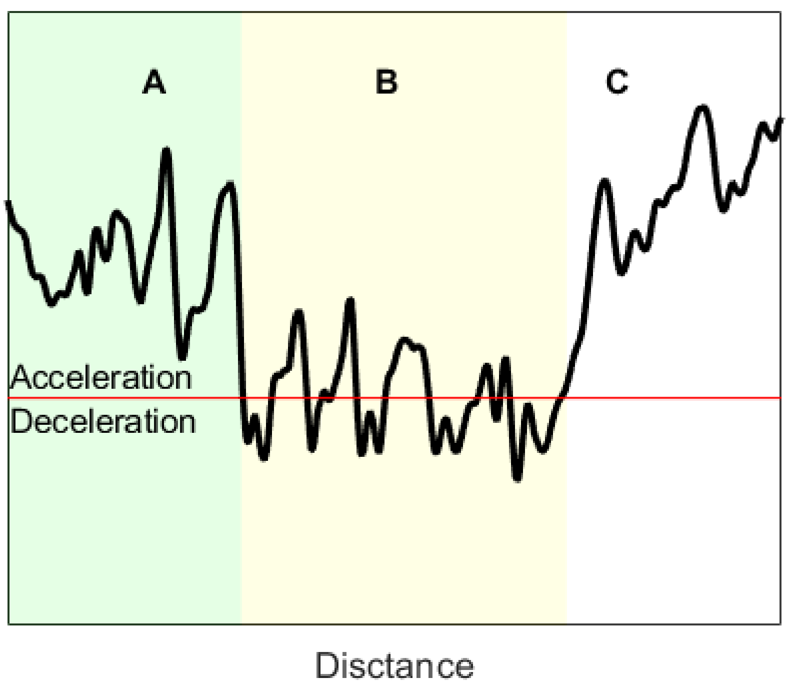

Figure 7.5: Pattern of skater without relay exchange

The push during the exchange

Before analysing the acceleration patterns of the push, the push during the exchange is analysed and divided into three different groups: Initial contact (Figure 7.6 - A.), start push (Figure 7.6 - B), end push (Figure 7.6 - C).

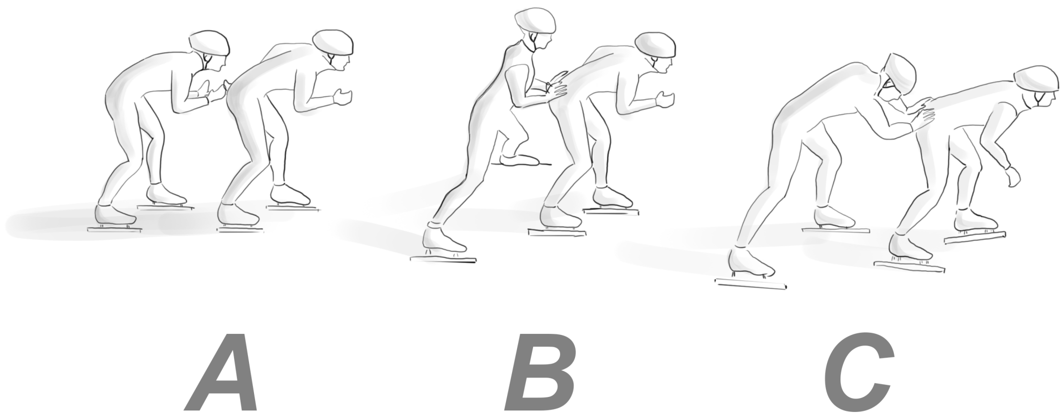

Figure 7.6: Three phases of the relay exchange A: Contact, B: Start of the push, C: End of the push

(A): Important to note is the body position and the orientations of the skates. In zone A, both the skaters have their centre of gravity above their skates and both skaters parallel in a forward direction.

(B): At the start of the push(B) the pusher positions his skates in a V-shape to achieve more grip on the ice for the push. The pushing skater puts his mass into the push, causing his centre of mass to become in front of his skates. The pushed skater is still in the same position with the skates parallel.

(C): The push ends with the lost of contact between the skaters. The pushing skater has to end the V-position of his skates in order to recover a balanced position after the push. His centre of mass is still in front of his skates, causing a forward momentum of the upper body after the push that has to be absorbed by the skater, shown in the . The pushed skater starts directly after the push with his first stride.

Pushing skater acceleration data

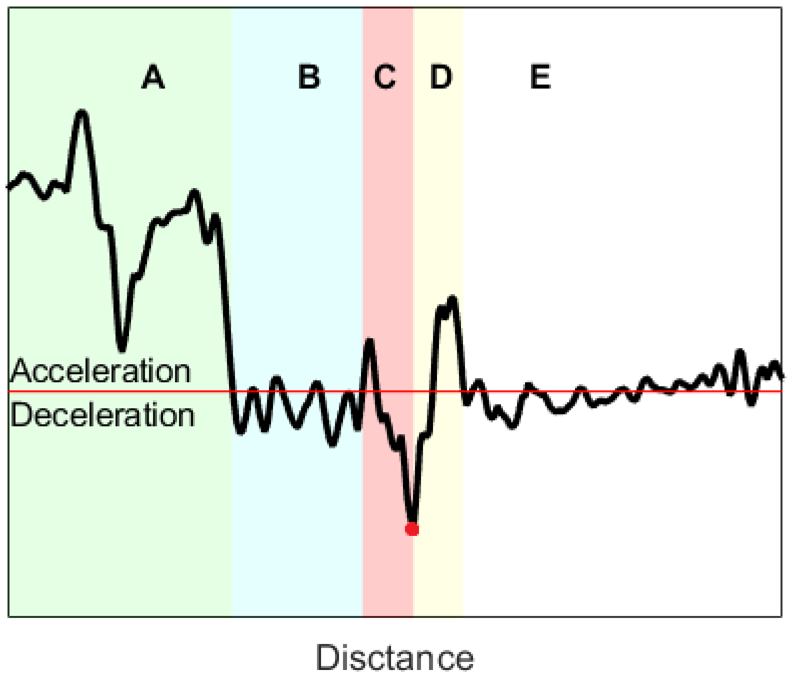

Figure 7.7: Pattern of pushing skater

This acceleration data had the most recognizable pattern. From halfway the entering corner, to halfway the exit corner, six zones were recognized within most of the data.

- The pattern starts with the exit corner accelerations.
- After the corner, a rapid decline in acceleration was visible. This zone was identified as the initial contact of the two skaters. Depending on the velocity synchronisation of the pushed skater, this area would be around or slightly below the zero acceleration line (red line). The better the velocity matching, the more horizontal and near the zero acceleration this area would be.
- After initial contact between the skaters, the pushing phase starts. This push is most recognizable by the large deceleration of the pushing skater(red area). A small peak before the decline was often visible. After the initial contact phase, where both bladed are often parallel pointing in the forwards direction, the push is started by rotating both skates outwards in a V position to gain grip on the ice. After this rotation of the skates, the body will tilt forward due to its former momentum. This is rapidly absorbed by the arms and the pushed skater, but still causes the small peak before the larger deceleration. The pushing skater will start deceleration after this phase, where he transfers his kinetic energy to the other skater. This deceleration will continue until contact between the skaters is lost.
- After this push, the exchange is finished. The pushing skater acceleration data often showed a peak after the decline of the push. Camera images showed large tilting motions after the

loss of contact. Also a realignment of both skates happens in this phase. This forward falling motion indicates a not completed transfer of momentum during the exchange, causing the pushing skater to tilt forwards.

- Finally, the resting phase of the relay starts. The skater often staid in a resting posture. This data is for the result analyse less important, but played a major role in finding the relay exchanges within all the acceleration data.

Pushed skater acceleration data

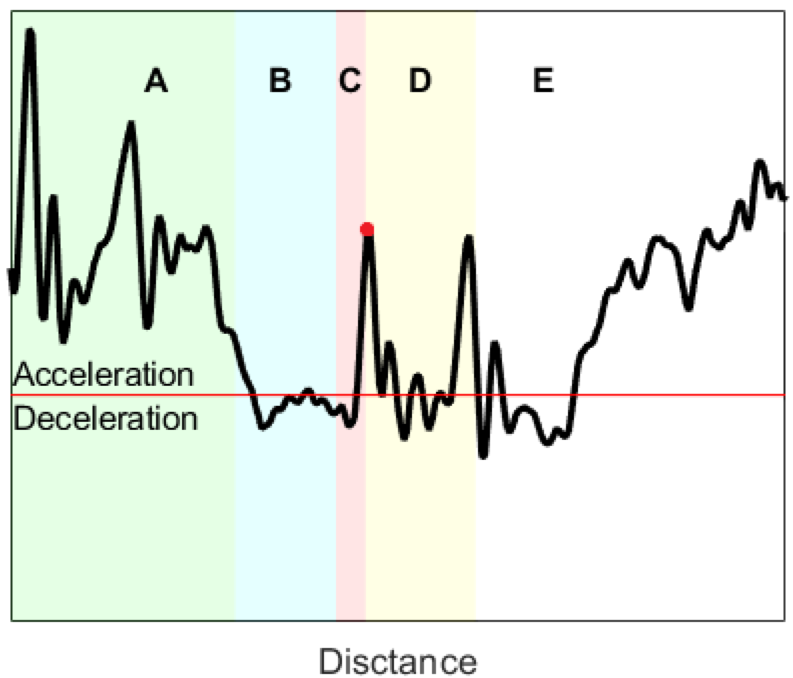

Figure 7.8: Pattern of pushed skater

The data for the pushed skater was less clear to interpret.

- The first entering corner had similar higher acceleration data like with the pushing skater data. However, the data from the pushed skater had a more spiky behaviour, caused by the smaller and less consistent corner radius during velocity synchronisation. In this last corner, the synchronisation of position and velocity is done, with sometimes radical take overs within the racing pack in order to match the correct skater.
- This was again followed up by an initial contact moment between the skaters where the acceleration were more around the zero acceleration line.
- The push was less recognizable with the pushed skater. The precise moment had to be found with the synchronous accelerating data from the pushing skater.
- Directly after the push, the pushed skater proceeds in two or three strides on the remaining part of the straight. These strides were often clearly visible shown as peaks with a set rhythm.

However, a difference in height between the peaks was not consistent. Even the peak of the push with the first stride was not consistently higher or lower than the other stride peaks.

- After several strides on the straights, the skater proceeds to the exit corner, often in one extended gliding motion on the outer skate. Within the last strides and this gliding motion, a new position in the racing pack is set. This could cause some deceleration's before entering the corner.