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OPTIMISING THE EXCHANGE: A REVIEW OF BATON PASSING STRATEGIES IN 4X100 M RELAY

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Abstract

The relay race, particularly the 4x100m event, presents unique challenges that integrate both physical capabilities and technical skills, especially during baton exchanges in high-speed conditions. This synthesis reviews three studies aimed at quantifying performance factors critical to successful baton handoffs and overall race efficiency.

The first part of the paper introduces mathematical equations to evaluate the technical aspects of baton exchanges, proposing a framework that allows coaches to identify weaknesses and predict team performance without complex procedures. Utilising data from elite and non-elite teams, this approach emphasises the potential for improving relay outcomes through targeted analysis.

The second part investigates the relationship between baton exchange time and the handoff point within the exchange zone, revealing that longer handoff distances correlate with shorter exchange times. Analysis of 230 exchanges among Polish national team sprinters indicates that while this relationship is significant, it accounts for only a portion of the variability in exchange times, suggesting the influence of additional factors on performance.

Finally, the third part employs mathematical modelling to determine optimal positions for baton exchanges, highlighting the complexity of the exchange process. Findings reveal that the ideal checkmark position varies for each exchange and is influenced by factors such as lane draw and free distance, with implications for coaching strategies to minimise disqualifications and enhance race outcomes.

Collectively, these studies underline the importance of both technical precision and strategic planning in relay performance, offering insights that could aid coaches and athletes in refining their approaches to training and competition.

Keywords: Baton exchange, relay, changeover technique, exchange moment, speed running.

Introduction

Relay races require athletes to make an individual effort, but with the scope of a collective performance. They are known to produce psychological tensions, causing passionate participation of spectators and participants. The relays are the highlight of athletics competitions.

The main objectives of the 4x100 m relay runners are to complete the run in the shortest possible time, receive and transmit the baton at maximum speed, and perfect their running technique and physical qualities at the highest possible level. The relay race occurs indoors and outdoors, running entirely on separate lanes. (McCloy C. & McCloy W., 2007)

The roots of this event go back to Greek antiquity when messengers who passed the baton became essential in quickly transmitting important information over long distances. The 4x100m relay has been part of the modern Olympic Games program since the 1912 edition in Stockholm, and since then, it has become one of the most iconic and watched disciplines in this sport.

Historically, the men and women of the United States have dominated this event throughout the 20th century, winning multiple gold medals at the Olympic Games and most of the IAAF World Championships. Carl Lewis ran as an anchor on the American relay teams that set six world records between 1983 and 1992. They were also the first team to break the 38-second record.

The current men's world record is set by the Jamaican team in the final of the 2012 London Olympics at 36.84 seconds. It represents the only team to have run under 37 seconds to date, Jamaica has dominated the men's event, winning two Olympic gold medals and four consecutive world championships. The Jamaican team also set the previous record of 37.04 seconds at the 2011 World Championships.

The relay is considered one of the most exciting and dynamic events in athletics. It is also the only event where the classification depends on the team's overall work, and it has other demands on the athletes, unlike other events. The baton exchange is a dynamic process where the two athletes transition the baton while running at high speed. Furthermore, the exchange is also blind, meaning that the receiving athlete does not see the baton when it is passed into his hand.

It combines the speed of the world's fastest sprinters with extraordinary timing, coordination, and teamwork. From the first sprinter's blistering start to the finish line, where the last runner exhausts his last energy reserves, the 4x100m relay is a suspenseful and thrilling race that keeps spectators in tension. But this is not the only reason why relays are the highlight of track and field events. They provide the sporting drama because of the frequent failure of the favourite relay

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teams, whose members fail to realise their running potential. The reason for this is often the lack of sprinters' specific relay qualities: concentration, reaction times, and perfect changeover technique, which ensure that the relay is changed at the highest possible sprint speed with optimal use of the changeover zone. The lack of understanding and coordination between runners, combined with a lack of training, can be the reason for relay tragedies in the past. (Struder et. al., 2023)

The baton exchange represents a crucial factor in determining the final result of a 4x100 m relay team. An efficient exchange significantly reduces time and increases the chances of winning. This article is designed to review the best and most effective methods for perfecting the relay changeovers. To study more deeply this theme, the following articles have been reviewed: ”The Baton Exchange during 4x100 m relay: a mathematical analysis” written by P. F. Radford and Ward-Smith (2003), ”Effective Baton Exchange in the 4x100a m relay race” by Zarebska, Kusy, Wlodarczyk, Osik and Zielinski (2021), and finishing with ”Running velocities and baton changeovers in 4x100 m relay exchanges ”written by Salo (2001).

The main competition rules regarding 4x100 m relay racing

The following simplified competition rules include the framework for technique and strategy, as well as for the conduct of the 4x100 competition:

Each exchange zone is 30 m long, with a starting line 20 m from the beginning of the zone. The start line marks the end of each 100 m section.

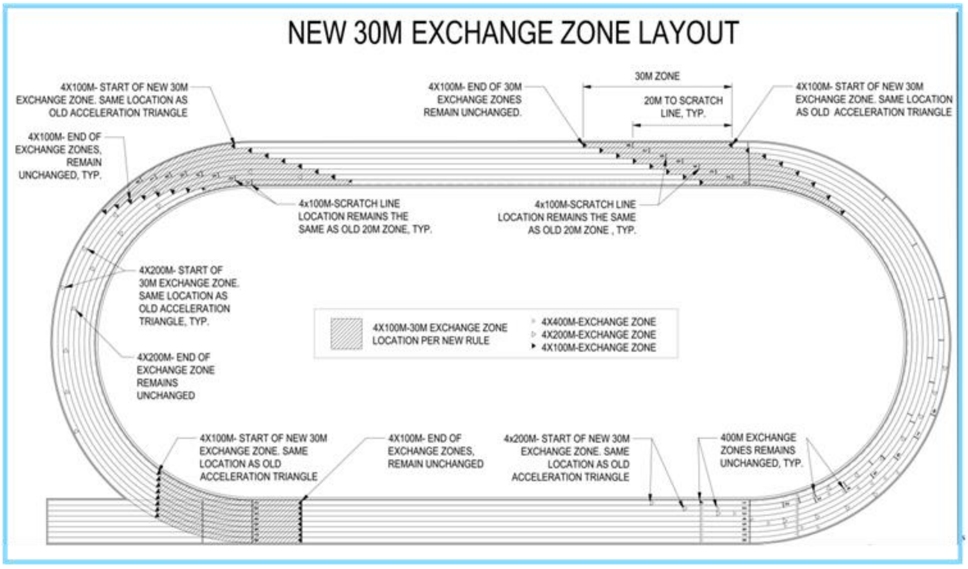

Figure 1. New 30 m exchange zone layout

The beginning of the exchange area is marked by a yellow "1", while an inverted yellow mark marks the end of it. (the viewing in each case being inside the lane). U14 athletes run 4x75 m while U12 athletes and under run 4x50 m. For the other changeovers, athletes are allowed to attach a sticky tape (maximum 5x40 cm) to their lane, which they use as a start marker. (Struder et. al., 2023)

The relay baton is a hollow, smooth tube with a round circumference that is usually made of metal. The circumference of a baton is 12-13 cm with a minimum of 50 g. The relay baton is worn during the entire race. Athletes are forbidden to wear gloves or other materials or substances on their hands in order to grip the baton better. If it drops, it may be recovered, but only by the athlete who dropped it and only if he obstructs no other competitor. Furthermore, not the sprinters but the relay baton must be in the changeover zone during the handover, which is the period when both sprinters have contact with the relay. Also, if leaving the lane, during or after the changeover, results in an advantage to the receiving sprinter or happens to impede other runners, he will be disqualified. Any type of help given to the upcoming runner, such as pushing or any other method, will result in disqualification. In addition, the general competition rules for running and sprinting apply.

The key issues regarding the baton exchange in the 4x100 m relay

The 4 by 100 m relay can be described as a thrilling event, although the baton exchange presents several challenges that can lead to dropped batons, slower times and disqualifications.

The first problem that may appear is regarding *time and synchronisation*. Predicting the speed is a crucial part of the exchange. The incoming runner needs to perfectly time their pass, while the receiver must accelerate into the exchange zone at the right moment. Both the incoming as well as the outgoing runners must maintain high speed during the exchange. The baton should be passed while both athletes are sprinting near maximum speed to minimise time lost during the handoff. (Zarebska et. al., 2021)

Optimal timing of the exchange is crucial. Research indicates that the baton should be exchanged as late as possible within the exchange zone, allowing the outgoing runner to accelerate for as long as feasible before receiving the baton. (Salo, 2001) A miscalculation can directly lead to missed exchanges. Also, clear communication between the runners is essential. Visual signals or verbal cues can help synchronise their efforts and avoid mishaps.

There are more baton passing styles, such as upsweep and down sweep techniques, regarding the technique and mechanics. Mastery of the chosen technique is vital to ensure a smooth and efficient transfer. The receiver's hand positioning and grip of the incoming runner on the baton significantly impact the exchange. Ideally, exchanges should occur within two strides and take less than one second. (Zarebska et. al., 2021)

Thus, incorrect positioning can hinder the process and increase the risk of errors. Physical factors related to the speed difference between the runners are also involved. The timing of the outgoing runner is critical. Misjudging the start can lead to disqualification or slower times. A significant speed difference between the runners, the incoming and the receiver can make the exchange more challenging.

This is why the incoming and outgoing runners must have closely matched speeds at the moment of exchange. This requires precise coordination and practice to ensure that neither athlete acts as an obstruction during the handoff. (Zarbeska, E. A., 2021) The faster runner will have to slow down, while the slower runner needs to accelerate quickly, increasing the margins for error. Also, as the race progresses, fatigue can affect both runners' speed, coordination and decision-making, increasing the likely of mistakes during the exchange. (Karlsson & Lunander, 2024)

Regarding the outdoor track season, there are also *environmental factors*: wind- can disrupt the runner's timing and make it harder to maintain a steady pace, affecting the exchange. The Tailwind effect, which blows in the same direction as the runner, can enhance their speed by providing an additional push. This is particularly beneficial during the baton exchange as it can help maintain momentum through the handoff process. A tailwind is measured positively (ex: +2.0 m/s) and can lead to faster overall times. On the other hand, a headwind creates resistance, making it harder for athletes to maintain speed. This can particularly affect the outgoing runner's timing during the exchange, as they may need to exert more effort to reach their maximum velocity while receiving the baton (women's outdoor track and field).

The track conditions, such as slippery or wet tracks, can reduce traction and increase the risk of falls or slips during the exchange.

Lastly, *psychological factors* such as pressure and confidence. The high-pressure environment of a major competition can lead to anxiety and tension, which can negatively impact the runner's focus and execution during the exchange. A lack of confidence in one´s ability to execute a clean exchange can lead to hesitation and indecision, increasing the risk of errors.

To address these challenges, teams typically invest significant time in practising baton exchanges, refining their techniques and developing effective communication strategies. By understanding and mitigating these key problems, relay teams can improve their exchange efficiency, reduce the risk of errors, and ultimately achieve faster times and greater success in the 4x100 m relay.

Secondly, they can influence the athlete's performance and team success. These factors include motivation, composure and trust, and anticipation skills. Regarding trust and communication, relay teams must have strong trust and open communication to ensure seamless handoffs. Each runner needs confidence in their teammate´s ability to deliver the baton accurately and on time. This trust can be developed through shared commitment and extensive practice to the team´s goals. Composure has to be maintained by athletes, especially in high-stakes competitions. The pressure to execute a flawless baton exchange can be intense, especially in the Olympic Games or important competitions. The ones who remain calm and focused under pressure are more likely to succeed. Another factor is team unity, essential for minimising conflicts, improving communication, and ensuring everyone works towards the same objectives. On the other hand, constant training at moderate intensity can be useful in pre-season, in micro cycles and regenerative sessions, and in injury recovery phases. (Padulo et. al., 2023)

Activities such as social events or team-building can help athletes connect on a personal level. Mental resilience refers to a strong sense of shared purpose that helps teammates support each other and maintain a positive outlook. The athlete's ability to anticipate further events is essential for initiating their run at the right time. Skilled athletes can adjust their movements using available information about their partner. (Chomienne et. al., 2024)

Discussions: World literature review

The first reviewed article, "The Baton Exchange during 4x100 m relay: A Mathematical Analysis" by Radford and Ward-Smith, aimed to examine the three baton exchanges during the relay race. Calculations were made for ideal or close-to-ideal positions for baton handoffs. The authors spotlighted the calculation of the checkmark position and exposed the complexity of the baton exchange mechanism, as there are not many studies regarding this subject. (Radford & Ward-Smith, 2003)

As is known, even at an elite level, like the Olympic Games or World Championships, many teams have been disqualified during the race. Checking the statistics until the early 2000s (1995-2001), 102 teams ran 182 races. 14.3% of the teams were disqualified. Besides that, 25.5% were eliminated before the competition finished. No other event in the athletic programme has such a degree of failure, even at an elite level, which shows that something is going wrong.

View studies investigated the technical analyses of the 4x100 m relay. Ward-Smith and Radford (2000) explored the factors that influence the overall time of the elite male teams. Among these factors were the 100 m performance of each athlete, the order in which they were allocated to run, the starting positions of the second, third and fourth legs and the point where the baton was passed or the lane where each runner starts. Also, the latter factor is significantly affected by lane curvature, which slows down runners and varies across lanes. Additionally, free distance represents the gap between the two runners, the incoming and the outgoing runners.

The article by Word-Smith and Radford (2002) and the practical experience on the track emphasise that the conditions of the baton exchange play an important role in determining the outcome of the 4x100 m relay. During the three baton exchanges, athletes need to avoid two unfortunate outcomes: disqualification by overrunning the takeover zone or dropping the stick. Running speed should also not be lost during the baton transfer.

To have an optimal exchange, the incoming runner's task is easy: He needs to run as fast as possible. The responsibility for an optimal transfer of the baton exchange rests with the outgoing athlete. The outgoing athlete who starts running too soon will leave the takeover zone before the baton arrives. Also, exchanging the baton at the highest speed is impossible, as it takes approximately 50 m for a high-level sprinter to achieve the maximum speed. (Ward-Smith & Radford, 2002).

The higher the speed, the less time is spent in the exchange zone, resulting in a more efficient baton handoff (Radford & Ward-Smith, 2003). In case an exchange happens after the 20 m acceleration phase, the receiving athlete is going to reach 89% of their maximum velocity. (Ward-Smith & Radfort, 2002)

The timing of the departure of the outgoing runner is crucial and needs some guidance, a checkmark, to start running at the right moment. The use of checkmarks is based on the idea that athletic performance is predictable and consistent, so experience gained in practice should transfer to the competitive field. Hence, the runner's performances during competition show that the performance of the athletes is slightly different, due to the baton exchange. This article investigated mainly the factors that are suitable for mathematical analyses and that affect the position of the checkmark in the three exchanges of the relay race.

Regarding the methods used, the study is built on previous work by Ward Smith and Radfort (2002) and Greene (1985), applying mathematical models in order to assess running performance on curves versus straight paths. They alternated the starting positions of the second, third and fourth athlete, the free distance or the position at the baton exchange. All these factors lead to a consequential movement of the mark that leads to a comprehensive range of data that has been calculated. It has been shown that running speed on a bend v is slower than on a straight one, due to the forces acting on the runner. Two-dimensional data has been introduced w=(v/v0)2w = (v/v_0)^2, which represents the normalised running speed, and r=Rg/v02r = Rg/v_0^2, which represents the curvature factor, with RR as bend radius and gg as gravitational acceleration. The relationship between w and r has been calculated as given in the equation w=r22+(r44+r627)1/3+r22(r44+r627)−1/3.

These equations have been used to calculate the effect of track curvature on sprinting speed, adjusting straight-line running speeds to obtain specific data. The authors optimised the different baton exchange positions, taking into consideration lane assignments, free distance at exchange, and the runners' order. Running speed on the straight exceeds that on the track curvature. The checkmark positions were mathematically analysed across different lanes and exchange scenarios.

The authors aimed to demonstrate the importance of the influence of the factors on the position of the checkmark. So the key findings of this study were: baton exchange requires several different checkmark positions depending on the lane, free distance and running speed. Furthermore, the first and third exchanges, which occur mostly on bends, show increased difficulty in comparison to the second exchange, which transitions from straight to bend. Also, the lane assignment impacts the overall relay time, as the curvature effect suppresses sprinting speed more in the inside lanes. The optimal free distance at baton exchanges was found to be around 1 meter, allowing smoother transitions and better speed retention. Relay teams that fail to account for these complexities have higher chances of disqualification or inefficient exchanges, explaining why 25.5% of relay teams at world championships failed to finish their races.

In conclusion, this study highlights the intricate details required for optimal relay performance, demonstrating that small adjustments in checkmark placements and exchange strategies can significantly influence the final race time.

The second reviewed article, "Effective Baton Exchange in the 4x100 m Relay Race" by E. Zarebska et. al., aimed to conclude the relationship between baton exchange time and the point in the exchange where the handoff is completed. (Zarebska et. al., 2021)

The objectives of this article were to analyse the effectiveness of baton exchange in this particular relay race, 4x100 m. Specifically, as mentioned, the research sought to determine the relationship between baton exchange time, noted with ET and the handoff point, noted with HP, within the exchange zone. The study aimed to provide insights into optimising baton exchanges to improve relay performance.

The article highlights the importance of efficient baton exchanges in sprint relay races, emphasising that a well-executed exchange could significantly impact the team's overall performance. This study was conducted on Polish national team sprinters, analysing 168 men's and 62 women's baton exchanges across an annual training cycle. The researchers measured the time the baton was spent in the exchange zone and the point of the baton handoff, using advanced timing systems. Other studies suggest that exchanges completed further in the exchange zone result in shorter exchange times, contributing to a better overall relay efficiency.

In this specific study, there were 27 participants, 16 men and 10 women, part of the Polish national team. During the training sessions, there were 68 men's and 62 women's baton exchanges recorded. The Brower Timing Systems (TC-System, USA) measurement system was used for precise timing. Regarding the statistical analyses, STATISTICA 13.1 software has been used.

More precise, linear regression analysis was performed to analyze the relationship between the overall 30–m exchange zone time and the change–over distance. The exchanges that did not comply with the regulations, like overrunning the exchange zone or baton drops, were excluded.

The results of this study showed a significant inverse relationship between ET and HP. Moreover, the further the baton exchange occured in the exchange zone, the shorter the exchange time. This correlation was stronger in woman ($r=-0.66$ to $r=-0.72$) than in men ($r=-0.45$ to $r=-0.68$). The coeficient of determination ($r^2=0.20$-0.52) pointed out that HP explains at most 50% of ET, suggesting other influencin factors.

In conclusion, the study confirms that a later exchange of the baton in the exchange zone leads to a more efficient handoff. However, since HP only accounts for a portion of ET different factors such as acceleration, sprinter coorination and technique must be considered. The researchers suggested that this type of measurement technique can provide coaches with valuable data to refine relay strategies and improve athletes' speed abilities. This study contributes to the understanding of relay dynamics and offers practical insights for optimising baton exchanges in competitive sprint relays.

The third and last reviewed article, "New trend for evaluating the technical performance of 4x100 m relay through predicting the team target record" written by Zaki, Sakr, Khafagy & Sallam (2024), aimed to introduce a new method for assessing the technical performance of relay teams. This study seeks to overcome limitations in previous research that primarily focused on optimising baton exchange techniques or mathematical modelling of relay races. Instead, the authors of this article propose equations that allow a quantitative evaluation of both physical and technical performance.

The main objectives of this study were to introduce this quantitative method to evaluate the technical performance of the relay teams. Secondly, provide equations to assess both physical and technical performance and help coaches identify weaknesses and predict target team records. Furthermore, it offers a simplified evaluation process that does not require complex procedures.

As a summary, the research addresses the importance of baton exchange efficiency in relay races. It proposes a mathematical model to evaluate performance and predict future records. By analysing elite and non-elite teams, the study highlights how technical execution impacts the overall results.

Further, regarding the used methods, the sample was divided into two. First, the elite teams, medal-winning from the Tokyo 2020 Olympics (Italy, Canada, China) and the Jamaican team. (World record holders). Secondly, the non-elite teams: 12 undergraduate students specialising in athletics, divided into three teams based on their sprinting abilities. The instruments, so the verification tests were: 100 m sprint test to assess individual speed, some relay race recordings to measure baton exchange efficiency and mathematical equations to predict relay performance.

The procedures used: First, the data from the elite teams was collected from the World Athletics website, and secondly, the non-elite teams were the students who competed in 100 m sprints, followed by relay races after a full day of rest. The formula suggested in the study aimed to predict relay records by subtracting 3.3 seconds from the sum of individual sprint times. The used performance evaluation equation (Predicted 4x100 m relay Record = $\sum$ PR 100 m $-\ \mathbf{3.3}$) measured the efficiency of the baton exchanges. The Spearman correlation coefficient: 0.36 indicated a positive correlation between predicted and actual relay records. The lost time percentage was used to assess the impact of baton exchange inefficiencies.

The results from the specialized literature showed that performance-wise, Italy had the best baton exchange efficiency (97.95%) and Jamaica had the lowest (97.47%) despite holding the world record. On the other side, the results of the non-elite team showed that the third team had the best technical performance, but needed to improve speed, the first team had strong physical abilities, but they needed a better baton exchange technique, and the second team required improvements in both areas.

As per this study, we can conclude that relay performance depends on both physical speed and technical execution. The baton exchange efficiency significantly impacts the results. Also, coaches can use the proposed equations to guide training strategies. It is also a practical tool for evaluating and improving the relay teams.

Conclusions

The relay performance is a balance between speed and precision. While physical speed is essential, the efficiency of baton exchanges plays a very important role in minimising time loss. A well-executed handoff within the exchange zone can make a significant difference in overall race time. Besides, other factors such as sprinter coordination, acceleration, and technique must also be optimised to achieve peak performance. Furthermore, strategic adjustments can significantly enhance relay results. Trainers can use mathematical models to evaluate technical performance but also guide targeted training strategies. Checkmark placements and refining exchange techniques can lead to measurable improvements in race efficiency, helping both elite and non-elite teams maximise their potential.

Authors` contribution

All mentioned authors have equally contributed to this paper.

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