Algorithmic approaches to quantify coordination between people in contact team sports

Elyse Levens



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Supervised by Professors Jeroen Bergmann and Timothy Denison

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Chapter 1

Introduction

1.1 Motivations

Coordination between people is inherently necessary when playing contact team sports. Differences in players' ability to coordinate with one another can influence overall performance. Athletes are required to repeatedly perform skilful actions at (near)-maximal efforts in team sports [1]. This requires athletes to accelerate and change pace and direction constantly in a semi-stochastic manner in response to changes in the game. There is therefore a need to investigate the overall interaction between players and move away from splitting it up into smaller units that focus only on an attack or defence [2].

Performance relies on many things, and among them is the ability to communicate and train in an effective manner. Repeated training of tactical plays enables athletes to improve their skill execution and decision making performance [3]. Rehearsing and practising plays can help reduce the length

of time a player takes on movement decisions. For team sports, those movement decisions rely heavily on the other players on the field (both teammates and opponents). The level of coordination across the whole system might differ depending on the need.

It has been suggested that attackers try to break the system coordination with their nearest opponents, whilst defenders seek to maintain it [4]. This indicates that the level of coordination between players is likely to influence the outcome in team sports. The need to ascertain or disrupt coordination can also lead to motion patterns that can increase the risk of injury. Injury incidence also relies on training, communication, and practice, all involving coordination between players.

Injury plays a significant role in the world of team contact sports. An injury can cost a player their career, and considering that the age of professional athletes continues to get younger [5][6], a career-ending injury can be particularly devastating. Contact team sports are one of the more injury-prone types of sports [7], and this is why analysis of injury risk is very important. Thus, many different methods have been developed to analyze injury risk [8] [9]. Of the existing injury risk analysis methods, coordination between players seems to be relatively understudied as a risk and predictive factor.

To study such a relationship further, a more technical definition of group coordination is required. The quantification of coordination between people will allow for the possibility of further improving performance and limiting injury rates. It will also allow for the application of computational methods to quantify team coordination based on relevant data. In other words, it will provide the opportunity to detect when group coordination occurs.

The quantification of coordination within a single body is not well-defined, let alone between multiple bodies. This is explained in detail in Chapter 2 (a systematic literature review). The methodologies of capturing coordination in quantifiable terms are not agreed-upon, nor applicable to a general population. A Coordination Game is therefore developed in this thesis, which fills this gap and provides an applicable methodology and definition for coordination between people.

Across research fields, different terms for coordination are used, such as: synchronization, control, cooperation, communication, and tactical behavior. Synchronization is an even broader term than coordination, which captured brain activity studies that were not applicable to the physical and biomechanical study of coordination in this thesis. Control was too broad as well, and captured simulation and non-physical bodies, that were also not applicable to this thesis. Cooperation captured a lot of robotics studies, which were not applicable to this thesis. Communication captured psychological and conversational studies, which were largely irrelevant to this thesis, and tactical behavior was entirely too specific and left out many studies that did not involve a "tactical" task. At the end of the term search, coordination seemed to be the best at capturing the behavior both within and between human bodies, and the methodologies that measure those behaviors.

The existing literature in coordination within a singular body is vast and unorganized. The existing literature in coordination between multiple bodies is few and study-specific. Coordination within an individual can be studied in many different ways: through the brain, through the muscles, through the joints, and between limbs. These subsections of studying coordination

within a singular body present even more methodologies and definitions that cannot be applied to studying coordination between bodies, because they are too specific to each subsection. In this thesis, I am studying interpersonal coordination, not intrapersonal coordination. Thus, the need for a broader, more applicable definition of coordination is evident.

Research has shown the potential suitability of applying correlation map analysis to accelerometer data to determine coordination between two people [10]. This simple algorithmic approach could be explored as an initial way of capturing group coordination. The performance of other, more complex algorithms can then be compared to the performance of this algorithm in the future.

The initial scenario that will be investigated, with the proposed computational method of correlation by association, will relate to defensive group coordination. Defensive behavior is mostly reactive and requires one player to react to the motor behavior changes of their opponent. Defensively, a player aims to prevent an opponent from scoring by shadowing or guarding the opponent closely [11]. As shown in a 1-on-1 basketball study, both players' anticipation and reactive movement must be considered for a successful defensive strategy [12]. The ability to correctly follow an opponent's movement can be captured by the concept of group coordination. This is the smallest possible group if only 2 players are considered. A computational method will lead to a quantifiable way to determine the level of group coordination, which can then be applied in future on-field research across a range of contact team sports.

This thesis first seeks to explore the current literature with regard to the

question of if coordination between players can be used to predict injury in team sport. The systematic review (Chapter 2) was used to determine the current state of play. This work required a broader definition for the term "coordination" in order to include group and team coordination as part of this review. It showed the need for more research within this area. An appropriate data set needed to be collected for computational approaches of quantifying group coordination to be tested. This required a novel experimental setup, during which motor behaviour between two participants could be accurately labelled as coordinated and uncoordinated (Chapter 3).

The proposed definition that captures a broader use of the term "coordination" and includes between-body studies is as follows:

Coordination: two (or more) factors working together during a functional task.

This definition is a necessary creation due to the existing study-specific and intrapersonal definitions and methodologies describing coordination.

In this novel reference dataset, inertial measurement units (IMUs) were utilized. IMUs possess three components: an accelerometer, a magnetometer, and a gyroscope. These components collect accelerations, magnetic fields for orientation, and angular velocities, respectively. The combination of these variables fill in the picture of human movement without utilizing video or GPS equipment [13]. Accelerometers are commonly used to quantify human kinematics and movement patterns [14]. Additionally, as previously referenced, accelerometers have been used in the past to determine coordination between two people conversing [10].

The IMUs were applied to participants' foreheads and sternums for data collection during the novel Coordination Game. This game was broadly inspired by a study completed by Kiefer, et al. (2017) [15], in which a set of 3 dyads (pairs) of participants cross a field space and try to avoid colliding with one another. The spontaneous coordination observed in this study can be compared to when opponents in a contact team sport game are on course to collide with one another on the field. The Coordination Game follows the broad concept of dyads crossing a space, except the relationship between participants is cooperative the whole time, rather than only in very small instances. The spontaneous aspect is repeated in the Coordination Game by not telling the participants where they're going or who is leading until the last moment. This way, participants are spontaneously and then continuously coordinating with one another across a game field.

Once this novel reference dataset is created, methodologies must be tested and applied to it. This is where simple and complex statistical techniques are used. The initial simple technique applied was correlation by association (Chapter 3). More complex analysis was required to apply coordinated and uncoordinated class labels to individuals (Chapter 4). In Chapter 3, coordinated and uncoordinated classes are designated as "most likely" and only over the course of multiple data sets. It is more useful to be able to designate classes to individuals and each instance of movement alone, which can possibly be done with machine learning classification techniques.

1.2 Research aims

There exists a gap in the existing research that revolves around coordination. There are currently no consistently-used definitions for coordination within a singular body, and, subsequently, no widely-used definitions for coordination between bodies. Because of this, studies in coordination (both intra- and inter-bodily) don't have any consistently-used measurement methods for coordination.

This research began in an exploration of what coordination could bring to injury prediction research. Due to the state of the existing research, the need for a consistent definition and measurement method for coordination both within a singular body and between many bodies is apparent. The research field of coordination should benefit substantially from the introduction of these foundational factors: definition and measurement method. Once it became apparent from the systematic literature review that the existing work in coordination was lacking, the course of this thesis changed from identifying coordination's role in injury prediction to defining and developing a measurement for coordination.

This research aims to answer multiple questions: 1) What research exists in the field of the relationship between coordination and prediction of injury? 2) Can coordination between people be accurately quantified? 3) Can inertial measurement units and simple correlation by association alone quantify group coordination? 4) Can more complex methodology such as machine learning classification models be used to accurately classify coordination and non-coordination? In this research, a definition and a reference dataset have

been developed, and each was tested.

Sports coaches, human kinematics researchers, and emergency/injury unit workers are among the people who could use this methodology to improve their work. For grass roots sports, inertial measurement units (IMUs) are among the cheapest tools to use for measuring coordination, as opposed to GPS units and video camera setups. For people who work with human movement, this novel Coordination Game methodology will allow them to quantify coordination between people on a generally applicable scale, as opposed to a study-specific measurement that cannot be applied elsewhere. For emergency and injury unit care workers, the Coordination Game and its measurements might allow for analysis of an injured person's coordinative capability. This could be used to diagnose an issue or help build a physical therapy routine.

A limitation of this work is that only 22 participants were able to be recruited, and only 14 participants' data was useable. The other data was unusable due to the IMUs falling off, the IMUs being calibrated incorrectly at the beginning of collection, or the participant(s) not disclosing a motor disorder prior to collection. Since this is a control dataset, the motor disorder participant(s) could not be included in this research. Another limitation is the tools used. The IMUs provide an easy and approachable method of collecting human movement information, however it might have been useful to have high-quality, multi-angle video data as well. Video data was collected, but only from one angle, to be used to check against the IMU data. Finally, a secondary observer was present for half of the data collection. It would have been preferable to have this secondary observer present for the entirety of the data set, for better validation purposes.

1.3 Thesis outline

In Chapter 1, the background, research aims, and limitations to the study have been explained.

In Chapter 2, a systematic literature review is provided, exploring the research question: Can coordination be used to predict injury? The absence of a concrete and agreed-upon definition for coordination is shown, alongside the absence of a generally-applicable coordination measurement method. A broadly applicable definition of coordination is developed.

In Chapter 3, the Coordination Game is developed. A control dataset is collected and analysed using a simple correlation by association method (Pearson correlation coefficients) and IMUs on pairs of participants. A general range of Pearson correlation coefficients is shown to classify whether a pair of participants are most likely coordinated or most likely uncoordinated; however, the classification of coordination is not concrete per person with this methodology, only with multiple tests of multiple participants. A more complex methodology must be tested.

In Chapter 4, machine learning classifiers are utilized to classify segments of coordinated and uncoordinated tasks, specifically, the Support Vector Machine (SVM) Kernel and the coarse K-nearest neighbours classifiers. These classification methodologies did not perform as well as expected, only obtaining testing accuracy scores of 62.1% and 55.6%, maximum. Further implementation of classification methods should be explored, as only the surface of machine learning has been delved into in this work.

In Chapter 5, an overview of this research and essential future work is

discussed.

Chapter 2

Can coordination be used to predict injury? A systematic literature review*

* Submitted for publication in *Journal of Science and Medicine in Sport (JSAMS) Plus* with co-authors Joseph Russell (Department of Technology and Innovation, TEK, University of Southern Denmark, Denmark), Timothy Denison (Department of Engineering Science, University of Oxford, England), and Jeroen H.M. Bergmann (Department of Technology and Innovation, TEK, University of Southern Denmark, Denmark). Currently awaiting peer review.

2.1 Abstract

Background Predicting injury is important for better managing those engaged in physical activity. It has been suggested that (motor) coordination is associated not only with performance, but also with injury. This systematic review explores the link between coordination and injury prediction.

Methods Articles were extracted from PubMed, Scopus, and Web of Science and assessed by two reviewers using a structured framework. The quality of each included article was scored and information was extracted with respect to coordination definition and injury location.

Results The review found 33 articles covering a total of 3070 volunteers. Most articles (n=27) achieved at least a "fair" scoring on a modified version of the Downs & Black critical appraisal checklist. The lower limb was studied in just over half of the included articles, with anterior cruciate ligament (ACL) injuries specifically explored in 6 of those. The sample populations included mainly young male participants with an average study population age of 26 years. It was noted that "coordination" was covered by a range of different terms, indicating a lack of consistency in the description of it. Most articles concluded that coordination could predict injury.

Discussion This review shows that coordination could be used to predict injury, but caution should be taken considering the use of different terms and definitions for coordination and the relatively small amount of studies in this field. The use of the term "coordination" is not agreed upon within the literature, which limits the generalisability of the findings across applications. Two major participant biases (gender and age) were discovered, which need

to be addressed to increase the validity of the findings for sports medicine. In summary, the link between coordination and injury prediction must be further explored to bridge the gap in our understanding of coordination and its clinical importance in injury prevention.

2.2 Introduction

Human health is positively influenced by participation in sport and exercise, which is important as inactivity levels are rising world-wide [16]. These things are, in turn, greatly affected by the incidence of injury. The ability to predict injury can directly inform prevention strategies, and there is some suggestion that coordination and injury are linked [17][18]. Although some of this work shows that better coordination implies lesser injury rate [19], there are studies that indicate better coordination implies higher injury rate [20]. It remains unclear to what extent coordination can act as a predictor of injury.

It has already been suggested that (motor) coordination is linked to changes in executive function and cognitive control [21][22], and injury risk is often being investigated with coordination tests [23][24][25][26][27][28]. It was also determined that there is a link between a person's performance in a coordination variability test and their likelihood of injury during sport [29]. These findings together would suggest that coordination could play an important role in injury. However, no comprehensive review has yet been conducted to determine what evidence exists that supports a linkage between coordination and injury.

The term "coordination" possesses a multitude of definitions across different fields of research, including physical therapy [30], neurobiology [31], psychology [32], and sports [33]. In physical therapy, coordination can be called "motor coordination" and is defined as one of the components that make up the "postural control system" [30]. In neurobiology, coordination

can be called "motor skills" and is defined as activity in different regions of the brain [31]. In psychology, coordination can be called "coordination patterns", and "movement variability", and is defined by entropy measures and as "features" of sensorimotor system operations [32]. In sport, coordination can be called "coordination/movement variability", "motor capability", "motor control" [33], "group performance", "interpersonal coordination", "movement coordination", and "coordination dynamics" [34], and all of these terms are defined as "the ability to gauge exertion accurately" [33] or "behavioral flexibility" or "symmetric relation" [34]. In the field of movement science (and biomechanics), "coordination" does not possess a concrete definition nor a definition that is widely applicable to research investigating coordination, or similar terms to coordination. [35][36]. Disagreement, or lack of clarity, of the definition of a term leaves space for miscommunication and doubt. A clear yet broad definition can potentially be used to avoid such miscommunication. After an investigation into the past (Bernstein 1987 [37]) and current (Kimura et al. 2021 [35]) definitions used for coordination, a broader, multi-body definition is proposed: *two (or more) factors working together during a functional task.*

Clinically speaking, studying coordination could provide a wider outlook on injury risk factor identification. Kimura et al. state that since the musculoskeletal system is so interconnected, "it is almost impossible to identify the function of each element in isolation during a whole-body movement" [35]. This is why coordination between elements is necessary for proper study of risk factors involving the injury of individual elements as well as a combination of elements, e.g. the study of coordination between individual bone

segments or between entire bodies.

Coordination is a prevalent concept in sport medicine, alongside injury [38][39][40][41]. However, the implication of coordination being involved in general injury prediction has not been explored. This systematic review asks whether coordination, as broadly defined as possible, can be used to predict injury. This is an important clinical question, as evidence of coordination as predictor for injury allows for potential new preventative measures. This review will also investigate the definition of coordination used in the included papers. The proposed definition is built upon these existing definitions and might provide researchers and practitioners to better communicate their work across domains. This broader definition may also lead the field of sports medicine to study coordination outside of an individualistic context.

2.3 Methodology

Design

This systematic review was conducted using all relevant articles discussing the utilisation of coordination to predict injury. Here, coordination is broadly defined as *two (or more) factors working together during a functional task*. An injury, as defined by Medline Plus and the Agency for Healthcare Research and Quality (AHRQ), is described as "damage to your body" [42][43]. Prediction is used here to estimate the probability of an injury occurring as a result of coordination. Two authors independently assessed all articles from the search and identified relevant articles based on the abstract and title (Appendix Supp. Table S1). Any disagreements between reviewers was

discussed until a common answer was reached. Relevance was decided based on the presence of all inclusion criteria, specified in Section 2.3.3.

A modified and verified version of the Downs and Black critical appraisal checklist [44] was used to assess the quality of the full-text articles retrieved from the initial abstract relevancy check, and this assessment was completed by the main researcher. One question from the original D&B checklist [45] was added to the modified checklist, question number 18, since it offered a statistical analysis method relevancy check. The final, modified D&B list included questions on reporting (items 1, 2, 3, 5, 6, and 7), external validity (items 11 and 12), internal validity - bias (item 20) and internal validity - confounding/selection bias (items 21, 22, and 25) (more details are given in Appendix Supp. Table S2).

The articles were scored based on three response types: "yes", "no", and "unable to determine". A "yes" designated a score of 1 for that question, and a "no" or an "unable to determine" designated a score of 0. The scores were labelled as follows based on their summed value: $\leq 7 =$"poor", $8-9 =$ "fair", $10-11 =$ "good", and $12-13 =$ "excellent". These labels were calculated based on the scoring given in a previous study [46]. Hooper et al. calculated their scoring based on the original 27-question D&B checklist, so the scoring was re-calculated for this review's modified, 13-question D&B checklist.

This critical appraisal checklist is used to assess the quality of both randomised and non-randomised studies within health sciences [45]. This systematic review followed the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) checklist [47] (Appendix

Supp. Tables S3 and S4).

Data sources

Articles were exported from the PubMed, Scopus, and Web of Science: Core Collection databases. The following terms were used in the database search: (Coordination OR Coordinated OR Coordinate OR Synchronization OR Synchronisation OR Synchrony OR Synchronized OR Synchronised OR Synchronism) AND (Pain OR Injury OR Damage OR Trauma) AND (Prediction OR Predict OR Predicted). An initial scan of the articles discussing coordination and prediction of injury revealed that the terms "coordination" and "synchrony" were commonly used. The articles collected from this search included publications up to and including March 2025.

Eligibility criteria for selecting studies

The inclusion criteria for the search were as follows:

1. Must include use of "coordination" in a relevant manner, such that two (or more) factors work together during a functional task;

2. Must include use of "pain", "injury", "damage", or "trauma" in a relevant manner, with the given definition of injury: "An injury is damage to your body. It is a general term that refers to harm caused by accidents, falls, hits, weapons, and more" [42][43];

3. Must have human participants in the study;

4. Must be written in English or translated into English;

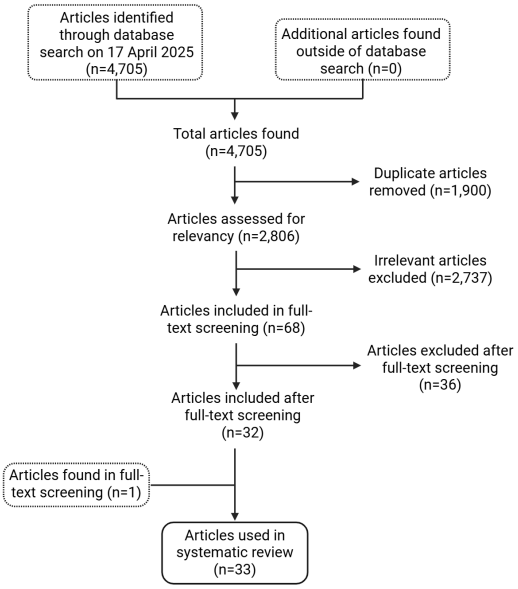


Figure 2.1: Flow chart of the decision process of systematically including articles in this literature review.

5. Must be peer-reviewed.

2.4 Results

Article Selection

The articles obtained from the databases totalled 4,705 (Fig. 2.1). Of those articles, 1,900 were identified as duplicates, which left 2,806 unique articles. A total of 68 articles met all abstract criteria and were included in the full-text analysis. Then, 32 articles met the full-text inclusion criteria. One additional relevant article was identified during this stage through inspection of the bibliography. A total of 33 articles were included in this systematic review.

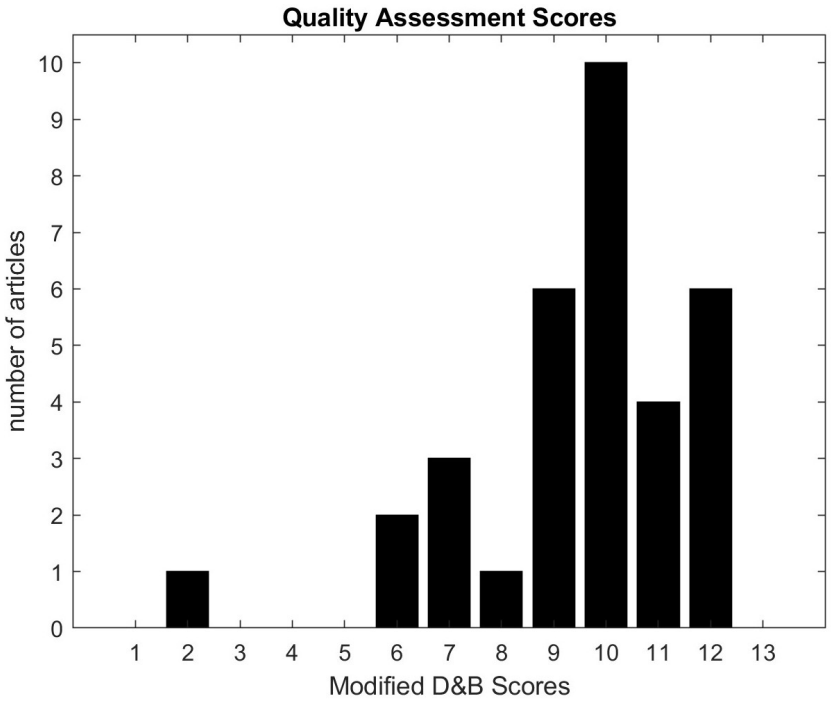


Figure 2.2: The scores of the modified D&B table range from 0 to 13, with ≤ 7 labelled "poor", $8-9$ labelled "fair", $10-11$ labelled "good", and $12-13$ labelled "excellent" [46].

Quality Assessment

Of the 33 articles included in this literature review, 27 articles scored between fair and excellent quality, with 6 articles scoring poor quality (Fig. 2.2). To recall, these scores are based on questions regarding reporting, external validity, and internal validity in two parts: personal bias and confounding/selection bias. The full table of scoring per article per question can be found in the Appendix Supp. Table S1. Common questions which scored poorly were associated with external and internal validity (Appendix Supp. Table S1).

Injuries

Multiple injury locations appeared in the extracted articles: lower back, anterior cruciate ligament (ACL), hamstring, lower limbs (non-specific), head/neck, hand, and whole body general (non-specific). Figure 2.3 shows two more "general" locations identified in the articles: the whole body, and the lower limb. Alongside the lower limb (general) articles, of which there are 4, are 6 articles discussing the ACL and 4 articles discussing the hamstring, specifically. As such, there are a total of 14 lower limb articles. Additionally, alongside the whole body (general) articles, of which there are 8, are the remaining 25 articles that specify injury location, for a total of 33 articles. This injury review involved a mix of sports-related injuries and non-sports related injuries.

Rommers et al. (one of the articles extracted in this review), ranked the most common injury locations based on occurrence in their data set of 734 participants [48]. Of the 368 injuries that occurred in Rommers' study, the three most common injury locations were found to be the knee (22.0% of all injuries), hip/groin (19.6%), and thigh (17.1%). Of the 33 articles extracted in this literature review, the most common specific injury locations were the lower back and the ACL.

Participant Information

Across the 33 extracted articles, there were a total of $3,070$ participants. As shown in Appendix Supp. Table S1, $2,166$ were male and 904 were female, giving a participant pool of 70.6% male. 11 of the 33 articles had *only*

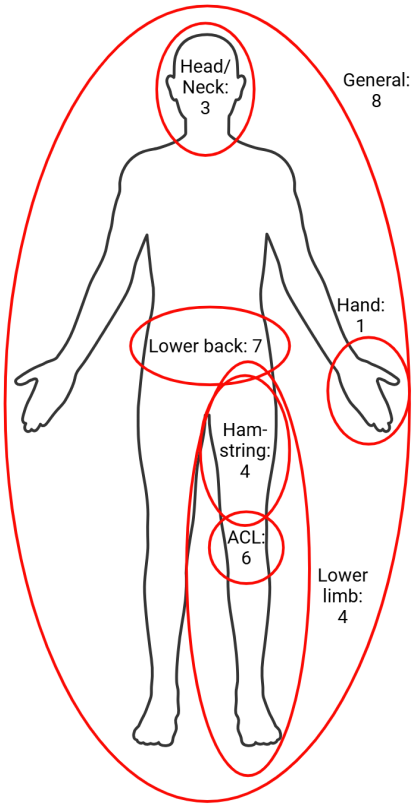


Figure 2.3: The injury locations specified in all articles extracted for this literature review. The injury locations circled on the left side of the body are also reflected on the right side of the body in all articles - the single-side is used in this figure for visibility.

% of participants per injury location	# of articles
37.0% general	8
22.0% lower back	7
20.7% ACL	6
7.6% head/neck	3
6.9% leg (general)	4
5.0% hamstring	4
0.8% hand	1

Table 2.1: The percentages of participants versus their respective injury locations per paper. The percentage of participants per number of articles is nearly matched, other than the lesser head/neck articles with the higher percentage of participants.

male participants. Another 14 articles had a majority male (> 50% male) participant pool. The ages in the articles (excluding the article discussing newborns) ranged from 8 to 81 years old. Each article presented a mean age. These means had a mean of 26 years of age and a standard deviation of 5.2 years for all participants in all studies. The median of the means of the extracted articles was 23.1 years. In Table 2.1, the number of participants per injury location is approximately proportional to the number of articles covering each location, apart from the head/neck location. It is relevant to note that a majority (20) of the articles extracted in this review come from the year 2022 and later.

Coordination

There were many different terms for coordination used across the articles extracted in this review, as shown in Figure 2.4. Two of the columns in this figure, "specific" and "general", have even more terms within them. The specific column (with 4 articles in it) uses terms such as "technical-tactical"

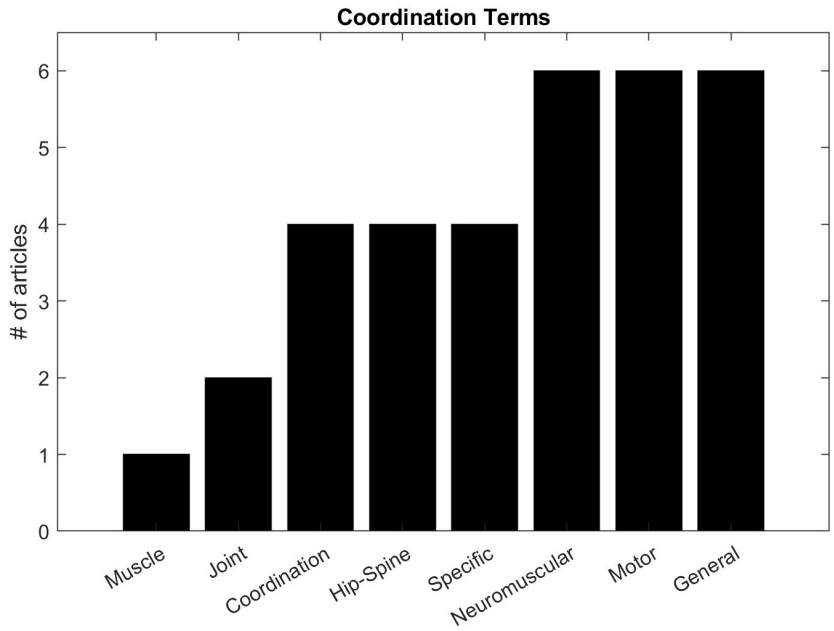


Figure 2.4: Terms used to substitute the term "coordination", and the quantity of articles that use those terms. Some papers utilised the singular word "coordination", which is shown in the third column from the left. Some papers used "specific" types of coordination (the fifth column from the left), including "technical-tactical" coordination, running coordination, hand-eye coordination, and the coordination of respiration and swallowing. Other articles used very general terms, including gait, movement coordination/coordinated movement, general movements, executive control, and coordination variability.

coordination and the coordination of respiration and swallowing. The general column (with 6 articles in it) uses terms such as movement coordination/general movements and coordinated movements. Most articles (21 of 33) did not have a description/definition of the coordination term used (Appendix Supp Table S1). Most articles (26) concluded that coordination could be used to predict injury, with 2 articles concluding that they were uncertain of coordination's role with predicting injury and 5 articles concluding that coordination cannot be used to predict injury.

2.5 Discussion

This systematic review included 33 articles which ask the question: can coordination be used to predict injury? Of these articles, 6 were designated "poor" quality from the modified Downs & Black quality assessment questionnaire. The rest (27 articles) scored between fair and excellent. Care should be taken with the results obtained from papers that score low in terms of quality. However, similar conclusions were obtained in the articles regardless of quality. Interestingly, but not surprisingly, the common questions that most articles missed were questions regarding external and internal validity. This implies that the results might not be generally applicable outside of each study.

Injury locations were centred on a few places, including the lower back/ lumbopelvic region and the ACL as the most commonly investigated injury locations (Table 2.1). According to Rommers et al., these location investigation choices fall in line with the most common injuries in sport: the knee, hip/groin, and thigh [48]. This also matches with the number of papers discussing each common injury location alongside the number of participants who obtained those injuries during these studies (Table 2.1). It seems that the studies reflect the incidence rates found in sports, with relatively little consideration of the predictability of the injury locations using coordination measures.

The included studies in this review majorly favoured male participants, with 70.6% of the total participants in all 33 articles being male. A third of the articles used *only* male participants. These are exclusionary datasets.

This means that the injury statistics and results from these papers are not easily generalisable to women. It is known from previous research that women are more prone to ACL injuries [49] [50], which was one of the main injury locations investigated in these articles. The 6 articles that worked on ACL had better distribution of gender, with approximately 60% female and 40% male. However, the other injury locations were not well-distributed: lower back with 25% female and 75% male and general with 10% female and 90% male. This imbalanced distribution makes it very difficult to take these findings forward to inform real-world policies in sport medicine.

There was also an imbalanced distribution of ages included in these studies. The range of ages investigated included years 8 to 81. However, the mean age among all 33 articles was 26 years, with a median of 23.1 years. Many of these articles investigated specifically sports (23 of 33 studies). The average age of a sports participant is 10-14 years old [51]. Thus, there is a great need to explore this question within a younger study population. Furthermore, more than 20% of sports participants are between the ages of 30 and 75+ [51], which means that there is also a great need to better understand the ageing population that remains healthy through sports participation. It is important to understand how injury incidence progresses/changes over the period of a lifetime, and the literature surrounding it should include proper representation of age.

Nearly every article used its own term for coordination, ranging from neuromuscular control to lumbopelvic rhythm and motor functional performance. These terms were categorised in Figure 2.4 into 8 different types. In the same regard, most articles did not include a definition or description of

the terms used. Those that did, provided a description of the use of their chosen coordination term by applying study-specific methodologies within their definition. An example of this is in Butowicz et al.'s article, which used the term "trunk-lower limb coordination" and defined it with "joint coordination patterns lie on a continuum of potential solutions for balance stabilization" [19]. However useful balance might be to measure coordination, it can't be regarded as a full descriptor of coordination. There are many other aspects to coordination that should ideally be considered alongside balance, such as coordination variability, which, in Desai et al.'s article, was measured with running trials [52]. Each study also identified a new and different way to predict injury. For example, Rommers et al utilized a machine learning model and pre-season testing, while Tojima et al 2018 used the relationship between lumbopelvic rhythm and lumbar-hip ratio, and Vrbanic et al 2007 used balance index scores for predicting injury. Other studies, such as McLean 2005, utilized 3D kinematics of a jumping task. Another study, Tojima et al 2017, measured hip ROM as a predictor of injury. Even within the same research groups, different methodologies of predicting injury are utilized.

This wide range of study-specific terms and definitions (or non-definitions) makes it difficult to gather and review literature discussing coordination. There may have been articles that were missed in this review due to their exclusion of the terms synchrony or coordination within their article, even though they may be discussing them. A singular, broad, and generally applicable definition of coordination would make conversations surrounding it much easier. Regarding this, a relevant statistic from this review shows that most articles (20 of 33) in this coordination conversation were published in

and after 2022. The broader conversation surrounding coordination and its use in predicting injury might only just be starting, and having a concrete and agreed-upon broad definition of coordination will be useful in upcoming work.

Of all 33 studies included in this review, 27 articles were able to conclude that coordination can be used to predict injury (Appendix Supp. Table S1). Two articles concluded that their ability to predict injury with their application and definition of coordination was inconclusive, and 4 articles concluded that coordination is not capable of predicting injury. Each study utilized different methodologies to measure coordination and predict injury. Of the articles concluding that coordination is not capable of predicting injury, the methodologies of coordination measurement spanned sitting paradigms, hop tests, the Bruininks-Oseretsky Test 2 (BOT-2), and EEG measurements. Of the articles concluding that coordination is capable of predicting injury, the methodologies included gait analysis, tennis footwork, running with heavy loads equipped, jump-landings, and treadmill walking. There aren't any common methodologies amongst the positive-finding studies nor the negative-finding studies.

This lack of clarity on coordination's role in predicting injury may be due to the small amount of research done, or it may be because the different approaches to measuring coordination cannot be easily compared to each other, as well as a lack of standardisation of what is meant by coordination. It is evidenced by the majority of the articles concluding that coordination plays a role in injury prediction that further investigation is needed in representative participant pools, with as broad terms as possible regarding coordination, to

further establish the strength of this preliminary interesting finding. Further studies in this domain can help progress the fields of biomechanics and sports medicine.

2.6 Conclusions

More high quality research with representative participant populations is needed to robustly confirm the preliminary finding that coordination can be used to predict injuries. At the same time, a more standardised and broader definition of coordination should be adopted to more easily compare results obtained in future studies. The definition proposed in this review will be a good starting point for the development of field-wide understanding of coordination.

Chapter 3

Pearson Correlation Coefficients to Quantify Coordination Between People*

* Article submitted for publication in *Perceptual and Motor Skills (Sage Journals)* with co-authors Joseph Russell (Department of Technology and Innovation, TEK, University of Southern Denmark, Denmark), Timothy Denison (Department of Engineering Science, University of Oxford, England), and Jeroen H.M. Bergmann (Department of Technology and Innovation, TEK, University of Southern Denmark, Denmark). * Dataset "A four-sensor IMU-based dataset using two-player coordination game" submitted for publishing in Dryad (datadryad.org/) with co-authors Joseph Russell, Timothy Denison, and Jeroen H.M. Bergmann. Currently awaiting peer review.

3.1 Abstract

The coordination of movements between two or more people can be considered as "group coordination". This is an understudied subject, especially within sports medicine. Many methods exist which analyze a single person's coordination. However, the understanding of what exactly coordination means in quantifiable terms can vary widely within this field. Further understanding the definition of coordination and possible methods to assess motion between bodies is necessary to attempt the quantification of group coordination. The aims of this study are (i) to develop a reference dataset of coordinated and uncoordinated movements between people, (ii) to explore if simple correlation methods can be used to identify group coordination in this dataset, and (iii) to determine if this approach can support a more qualitative definition of group coordination.

In this study, a coordination game was created involving two people crossing a field to reach a goal while following and copying each other's movements. Pearson correlation and cross correlation coefficients were computed based on the 3D Euclidean norm of accelerometer signals obtained from an inertial measurement unit placed on each volunteer's chest. Multiple trials were obtained per pair of volunteers. Coordinated and uncoordinated events were found to be significantly different across all participants and trials. These events were mainly distinguishable when considered at a group level. These results imply that simple measurements can provide insights into group coordination and further exploration is warranted to develop more accurate methods for a case-by-case identification of coordination. The dataset used

in this paper is made available for further experimentation in this foundational area of research.

3.2 Introduction

Team contact sports (such as rugby and football) require great levels of highly complex coordination between players [53]. To perform well, players should have a good understanding of the movement patterns of both their teammates and their opponents, to help predict play sequences, optimise strategy, and possibly avoid unnecessary collisions. Despite this deep need for coordination between players in team sport, group coordination is not well-defined, nor understood in existing literature (see Chapter 2).

Coordination between people, or group coordination, is a newly explored field in sports medicine. The wide world of coordination studies spans fields such as neuroscience, psychology, and biology [54][55][56]. However, nearly all of these existing coordination studies observe single-body coordination. Very few studies have been completed that explore multi-body coordination [34]. There is work that looks at player trajectories to determine successful plays [57] [53], but these studies lack an underlying ground truth to establish if players are coordinated or not. This study aims to introduce appropriate ground-truth-based methods to support more robust explorations of group coordination.

A general but quantifiable definition of group coordination is necessary for further exploration of this aspect of team sport. The following definition inspired by past and current literature is proposed:

Coordination: two (or more) factors working together during a functional task.

The use of "factors" allows for broader assumptions to be made, such as

multi-body interaction, and the use of "functional" ensures that the task has purpose. This study aims to explore this new definition experimentally.

A 2017 study investigated the spontaneous coordination that occurs between pedestrians when crossing streets [15]. This experiment involved pairs of pedestrians crossing in a designated experiment space. The coordination game developed in this study (Section 3.3) is broadly inspired by the 2017 study. It provides a framework that allows for group coordination to be imposed in a controlled manner. This is an essential step for testing potential analytical tools that can help identify (or in the future even predict) the occurrence of group coordination.

This study will explore the movements between two participants. The relationship between the obtained signals will be calculated using Pearson correlation coefficients [58]. This correlation-by-association method seems to be the best path to start attempting to quantify coordination. Logically, if one individual's motion patterns are similar to another individual's motion patterns, they are likely to be coordinating with each other. Conversely, if the two sets of motion patterns are dissimilar, they are not likely to be coordinating with each other. Correlation can be used here as a measure of coordination, given that coordination is driven by forces, such as acceleration. The way human bodies interact with the world is through force interactions, such as the acceleration forces between two individuals. In this study, correlation coefficients will measure coordination between people.

It is important to continue to change both speed and direction when playing in team sports, which makes acceleration measurements particularly popular for measuring performance in sports [59][60]. The most widely used

location for the placement of the accelerometer in team sports is the chest [61]. A small chest-strapped Inertial Measurement Unit (IMU) that consists of accelerometers (measuring accelerations), magnetometers (measuring magnetic fields, e.g. direction), and gyroscopes (measuring angular velocities) can provide a suitable form factor for data collection. These are also very accessible pieces of equipment compared to GPS devices and camera setups. Using IMUs makes any implementation of this methodology easier and cheaper for every level of sport, from professional to grass-roots youth sports teams. This paper introduces a novel experimental approach to obtain ground-truth data for group coordination, which can be utilized to explore specific analytical methods. Pearson correlation coefficients are computed to explore how well group coordination can be identified by just considering the relationship.

3.3 Materials and methods

Recruitment and ethics

Participants were recruited via the University of Oxford's Engineering Science staff and students emailing list and poster distribution. 22 participants were recruited and included in this study. Each data collection session utilized two participants working together, which produced a data set size of $n = 11$. However, due to the sensor falling off the participant or the sensor being incorrectly calibrated, 4 tests were excluded, for a final data set size of $n = 7$. The ages of the participants ranged from 12 to 57 years, with a range of athletic experience from none at all to professional. The ideology of these

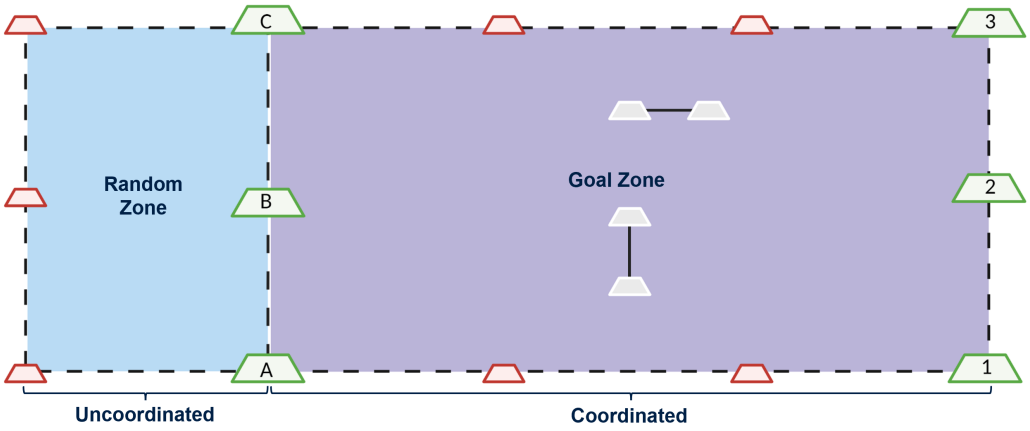


Figure 3.1: Experimental space for the Coordination Game. The red coloured cones are used to outline the space, the green coloured cones are goal cones (either Number Goals or Letter Goals), and the white cones with lines connecting them are used as gates. The left (blue) side is the Random Zone, where participants are not given a coordinated task, and the right (purple) side is the Goal Zone, where participants are given coordinated tasks to do together.

ranges was to find if this quantification of coordination could be generalised.

The Medical Sciences Interdivisional Research Ethics Committee (IDREC) reviewed and approved the protocol for this study, which can be found under the reference: R92954/RE002.

The Coordination Game

The experimental space contains two sections, the Random Zone and the Goal Zone (Fig. 3.1). The participants are in the Random Zone when they are not given a functional (coordinated) task. They are told to move about the Random Zone in an uncoordinated manner while trying to keep from noticing where their partner is in the space. The participants then move into the Goal Zone once they are given a functional task.

There are two roles in this protocol: the Leader and the Follower. The role of the Leader is to cross the Goal Zone, go through both white-cone gates, and reach the Number Goal on the other side. They are then tasked to come back through the Goal Zone, through both gates once more, and reach the Letter Goals on the edge of the Goal and Random Zones. The Leader is given the option to run, walk, jump, spin, or any other motion they choose, across the Goal Zone, as long as they go through both white-cone gates at some point on the way to their goal. They are able to go through both gates in either order, in any way they would like. This variation is intended to help keep the task from being repetitive and the participants from anticipating each other's movements. The role of the Follower is to repeat, or shadow, every movement the Leader makes while crossing the Goal Zone. This should happen as soon as the Follower notices the Leader has started moving. The idea of this is that if the participants are well-coordinated with each other, the Follower will move more similarly to the Leader than if they were not well-coordinated with each other.

The Coordination Game is based in the definition of coordination, which relies heavily on "a functional task". Once given a functional task, the participants are considered coordinated. Once told the functional task is complete, the participants are considered uncoordinated. This means that, in the case of this study, the task instructions are the main classifier of when coordination occurs. Coordinated movement could occur outside of task instructions, but that involves a different experimental setup and different research questions.

This coordinated task of crossing the Goal Zone is done 6 times per

round with differing Leaders. Each time, the Number and Letter Goals are randomly selected. The total number of coordinated tasks and uncoordinated tasks included in this study is 132, with $n = 66$ per class (50% coordinated and 50% uncoordinated).

Xsens DOT sensors (IMUs)

The IMUs used in this study are Xsens DOT sensors (Movella, Henderson, NV, USA). Within them are accelerometers, gyroscopes, and magnetometers collecting accelerations, angular velocities, and magnetic fields, respectively. The Xsens DOT sensors utilize the Xsens Kalman Filter core (XKFCore) algorithm for sensor fusion. This algorithm filters and processes the raw data before it is outputted. The initial collection of 5 of the sets of data used Euler angles for the orientation (magnetometer) measurements. These were converted to quaternions to avoid gimbal lock and loss of data [62]. Each participant wore one IMU on their chest and one IMU on their forehead using comfortable straps. The chest-mounted IMU data was chosen as it better described the body's coordination as opposed to the head-mounted IMU, which better described the attention-span of the body.

Data processing and analysis

A moving average was applied to the data for visualisation, which smoothed the noise of the step cycles. The euclidean norm was taken of the x, y, and z acceleration values for analysis of the full picture of the entire body's accelerative coordination.

Statistical methods

All analyses for this study were completed in MATLAB (R2025b). Pearson correlation coefficients obtained using Cross correlation functions (CCF) were visualised to observe any lag in human response time between the volunteers. The typical response delay between a human seeing and processing the movement before responding is approximately 0.2-0.3 seconds [63]. Therefore, a CCF with a lag time window of 3 seconds should capture the entirety of the lag between participants. The obtained coefficients were compared using a two-tailed t-test for both types of tasks (coordinated and uncoordinated).

3.4 Results

Visualization

The 3D Euclidean norm of the chest acceleration was used for calculating the relevant correlations. Mapping both participants' data on top of each other for an uncoordinated task and the subsequent coordinated task provided a visual representation of the difference (Fig. 3.2). However, coordinated and uncoordinated tasks were not consistently visibly distinct from each other.

The Pearson correlation coefficients, r, were found using cross correlation functions (CCFs) (Figs. 3.3 and 3.4). The lag time axis describes how much lag has been applied to the two sets of data (one set for each participant). At a lag of 0 seconds, the two data sets are laid directly on top of each other, exactly as the data was collected. In other words, at lag time 0, both data sets start at the first time stamp. At a lag time of 1 second, the two data sets

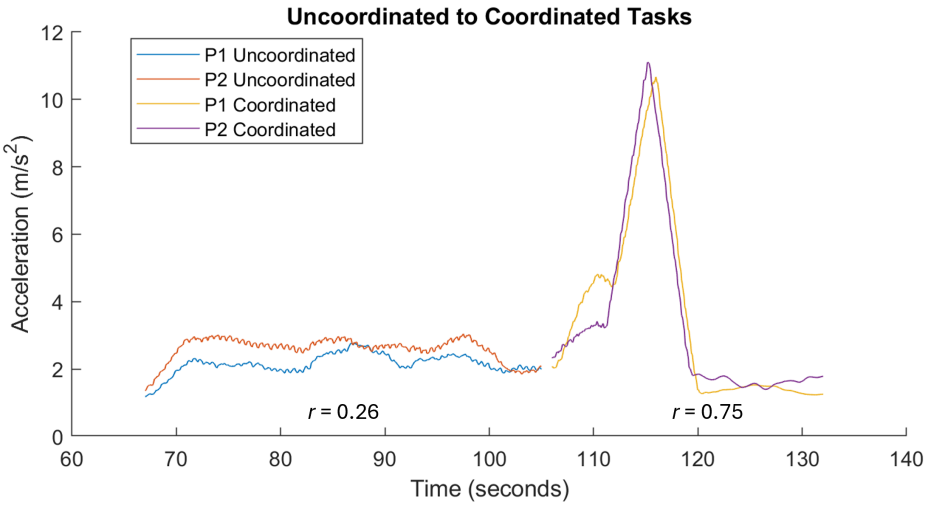


Figure 3.2: An example of the accelerations of the two participants over time is shown here in two sections. The first section (in orange and blue) is when the two participants were not coordinating with each other. The second section (in yellow and purple) is when the two participants were coordinating with each other. The Pearson correlation coefficient for each section is shown below each section ($r = 0.26$ and $r = 0.75$ respectively). The legend identifies accelerations as those of Player 1 (P1) or Player 2 (P2).



Figure 3.3: The cross correlation values were taken of all uncoordinated segments and averaged in this CCF graph. The solid line represents the mean and the dashed lines represent the central 95%. Given that each peak happens at slightly different lag times, the maximum of the CCF graph will be slightly lower than the mean maximum of the correlation coefficients. The mean maximum correlation value (the Pearson correlation coefficient) of these uncoordinated tasks was found to be $r = 0.19$ at a lag time of near 0 seconds.

are offset by 1 second. This means that while Player 1's data set starts at the time stamp of 0 seconds, Player 2's data is shifted so that it starts at the time stamp of 1 second. The peaks of cross correlation values always occur within 1 second of lag time, which is due to natural human response time. When Player 1 does a certain movement, it takes Player 2 approximately 0.2-0.3 seconds to see the movement, process it, decide to make the same movement, and actually make that movement. This causes the maximum Pearson coefficient to occur between -1 and 1 seconds of lag time on the CCF graphs.

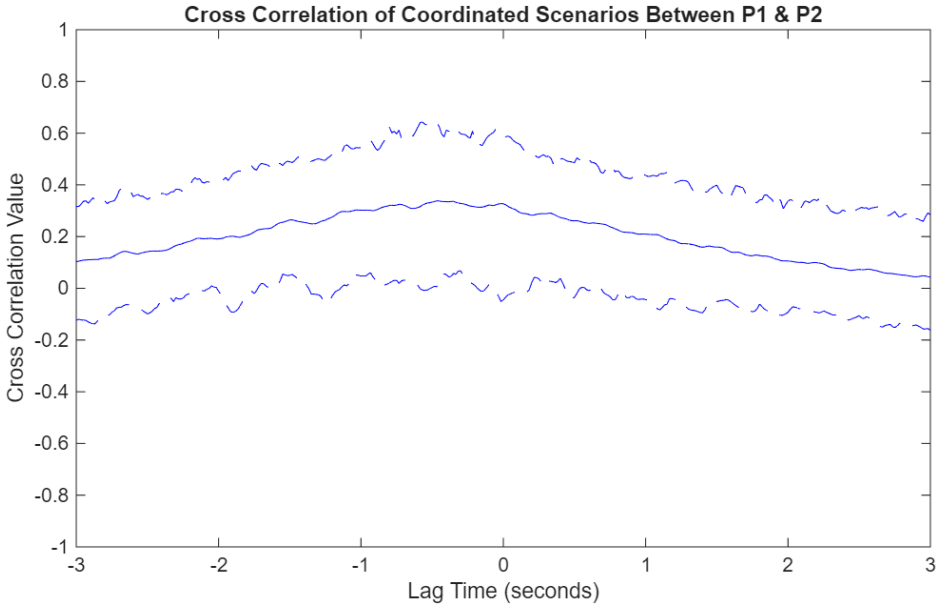


Figure 3.4: The cross correlation values were taken of all coordinated tasks and averaged in this CCF graph. The solid line represents the mean and the dashed lines represent the central 95%. The mean maximum correlation value was $r = 0.42$ at a lag time of near 0.

Scatter plots

The accelerometer data of Player 1 and Player 2 with zero time lag were plotted against each other in Figure 3.5 to observe the nature of the correlation. The scatter plot in A (uncoordinated) shows dense clustering near the origin, suggesting that when not given a coordinated task to complete, participants accelerate less. The scatter in B (coordinated) shows higher accelerations from both Player 1 and Player 2. This suggests that higher accelerated movements occur during coordinated tasks.

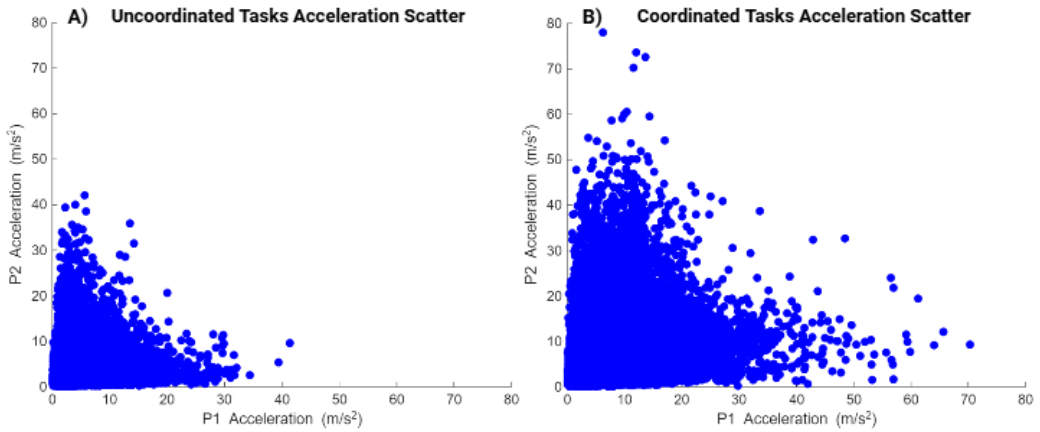


Figure 3.5: Scatter plots of the uncoordinated (A) and coordinated (B) tasks for all tests and participants.

Descriptive statistics

The mean accelerations of all coordinated sections (both participants) was 4.34 $\pm$1.49 m/s^2, and all uncoordinated sections had a mean acceleration of 3.03 $\pm$0.60 m/s^2. The average difference between P1 and P2 average accelerations during coordinated tasks was 0.22 m/s^2, and during uncoordinated tasks is 0.54 m/s^2. This difference was non-significant, with $p = 0.14$.

Pearson Correlation Coefficients

The peak Pearson correlation coefficients (r) were found through the cross correlation functions (CCFs). Of the data collected from the 7 tests, there were 66 validated coordinated sections and 66 validated uncoordinated sections. An r was found for each section and their means are displayed in Table 3.1. A two-tailed two-sample equal variance t-test was computed, through which a p-value of < 0.001 was obtained.

Coordinated		Uncoordinated	
Test #	Avg. Pearson Corr Coeff	Test #	Avg. Pearson Corr Coeff
1	0.45	1	0.16
2	0.57	2	0.13
3	0.44	3	0.19
4	0.25	4	0.23
5	0.27	5	0.20
6	0.57	6	0.24
7	0.39	7	0.20
Avg.	0.42 ± 0.12 s.d.	Avg.	0.19 ± 0.04 s.d.

Table 3.1: All Pearson correlation coefficients (r) for coordinated (left) and uncoordinated (right) tasks in 7 tests. "Avg. peak r" is obtained from the peak correlation coefficients from each scenario, averaged across all scenarios within each test. An equal variance t-test was calculated with $n = 66$ coordinated sections and $m = 66$ uncoordinated sections. A p-value of < 0.001 was obtained.

3.5 Discussion

The Coordination Game and the equipment used for it has allowed this study to test data collection for coordination between people. With this, different algorithms' capabilities of identifying classes of coordination can be tested. This methodology and a reference dataset have been made accessible for future work in this foundational area of research.

Typical human reaction time is approximately 200ms [63]. Initially, it was hypothesized that it would be necessary to account for this delay in the processing of the data, in order to synchronise the movements of the Leader with those of the Follower. However, it was observed that adding a 200ms lag between the Leader and the Follower actually reduced the strength of the correlation. Further investigation suggested this may be due to a "catch-up" speed of movement that the Follower does once they see the Leader start moving. While the 200ms of lag may appear at the start of the movement, the Follower is usually able to synchronize with the leader, removing the lag once the activity is underway. As the lag only appears at the onset of movement, a far larger fraction of the activity is spent without the lag than with it. As such, it was decided not to explicitly attempt to compensate for reaction time in the study.

The scatter plots show only weak linear correlations between participants during both coordinated and uncoordinated movements. This suggests that non-linear, more complex testing applications may be required to properly describe coordination between people, and this should be explored in future work.

Correlation is used in this study as an indication of coordination. The Coordination Game captures similarities of movement as well as the asynchronous catch-up covered by the lag time. Highly coordinated sporting actions can occur in both positively correlated and negatively correlated accelerations. Consider: teammates have decided on a tactic which involves them splitting to run in opposite directions on the field. Or, one teammate must slow in the exact space and time in which another teammate must accelerate. These are still coordinated movements between players. Both negative correlation coefficients and positive correlation coefficients were treated as coordinated. Most of the CCFs of the participants looked like Figures 3.3 and 3.4. However, there were some outliers, as seen in Table 3.1. In Test 4, the participants coordinated segments obtained a maximum correlation coefficient of 0.25, and the uncoordinated segments obtained a maximum correlation coefficient of 0.23. This small difference leaves the classification of coordinated and uncoordinated movement patterns between these particular people quite difficult. For this pair of participants, only "most likely" statements can be made regarding their coordinated segments throughout the Coordination Game. In other words, if a segment of movements produces a correlation coefficient of 0.25, the observing researcher can only state that the participants are "most likely" coordinated. Similarly, the participants in Test 5 obtained only a 0.07 difference between coordinated and uncoordinated segments.

There are a couple of reasons why this small difference between coordinated and uncoordinated correlation coefficients might be. The participants were not told to coordinate their steps, so it is possible that higher corre-

lation values could have been obtained if the participants had focused on coordinating their footsteps as well as general movements. The correlation could also be limited by human capability of accurately replicating movement. Some participants may not have taken the task as seriously as others, while some may just have poor coordination, which would be expected to show lower r values during the coordination sections. There may also have been some instances during random walking in which participants coincidentally move at the same accelerations without knowing, which look like coordinated movements. In general, there were more rapid changes of speed during the coordinated tasks in comparison to the random walking.

Section 3.3 shows that the difference in accelerations between Participant 1 (P1) and Participant 2 (P2) is non-significant for both coordinated and uncoordinated tasks ($p = 0.14$). Importantly, the difference in the average acceleration values is larger for uncoordinated sections. This means that P1 and P2 differed in movement speed more during uncoordinated tasks.

The average peak r value for coordinated sections was 0.42 ± 0.12 s.d., while the average for uncoordinated sections was 0.19 ± 0.04 s.d.. A p-value of < 0.001 was calculated, which implies statistical significance. Therefore, from these average r values, it was shown to be possible to distinguish between coordinated and uncoordinated sections. However, this distinction was not entirely reliable, given the outliers such as Tests 4 and 5. With this very basic application, it is possible to predict whether a section of acceleration data is more or less likely to be coordinated. Correlation values lower than 0.23 are more likely to be uncoordinated, while correlation values higher than 0.30 are more likely to be coordinated. Further testing with different applications is

necessary to be able to distinguish with greater certainty between coordinated and uncoordinated human movements.

3.6 Conclusions

A novel methodology and reference dataset have been developed and collected. These tools will be invaluable for the continuation of studying coordination between people. The first example of application of this methodology is made with simple Pearson correlation coefficients, which concluded that coordination between people can generally be identified within a dataset of at least 14 participants. Further applications are necessary to explore this foundational area of research in coordination.

Chapter 4

Classification Analysis to Determine Coordination Tasks Between People

4.1 Introduction

Coordination between people is sorely lacking both qualitative and quantitative research (see Chapters 2 & 3). Preliminary analysis with inertial measurement units (IMUs) shows that coordinated and uncoordinated movement patterns can be distinguished broadly with simple correlation analysis (Chapter 3). However, this analysis can only describe segments of motion between people as "most likely" coordinated or "most likely" uncoordinated. There is not a clear barrier between the two states per individual test, only over multiple tests. Therefore, a more complex analysis must be involved to further investigate the relationship between IMU data and quantifying

coordination between people.

Machine learning is a common methodology for classifying between states [64]. There are many different classifiers, including support vector machines (SVMs), nearest neighbors, kernel approximation, and neural networks. These classifiers were tested with a similar dataset from Chapter 3: a four-sensor based IMU-based control dataset, this time of 10 sets of participant pairs playing the Coordination Game (to be published: doi.org/10.5061/dryad.k0p2ngfp0). Briefly, the Coordination Game involves segments of uncoordinated and coordinated movements across a playing field, with one participant leading the other participant to specified places on the field. For more detail, please see Chapter 3, subsection 3.3.

SVMs are commonly used to distinguish between 2 classes of linear data. In this case, the two distinguishing classes are the coordinated class and the uncoordinated class. The data used in this study is nonlinear, so a kernel approximation was applied, which allows linear approaches to be used with nonlinear data [65].

K-nearest neighbors (KNN) classification is one of the simplest classification techniques. In a network of data, KNN will classify a data point (node) entirely based on its nearest neighboring nodes. No other operations are completed in this classification model, making it the easiest to compute [66]. In MATLAB (R2022a), a KNN classifier can be made coarse, medium, or fine. A coarse KNN was used in this instance to minimize overfitting.

In addition to these classifiers, Long Short-Term Memory (LSTM) was used to attempt to classify between coordinated and uncoordinated states. LSTM is a type of neural network classifier that is used to classify nonlinear

data with time-series analysis. Time series analysis is an important aspect to include for the Coordination Game dataset, since coordination occurs over time, not just at one single time point. In an LSTM, there are many parameters which can be changed to optimize the classification accuracy, including hidden units (hidden layers), epochs (the number of times the dataset is run through), and learning rate (step-size). LSTM uses hidden layers to compute operations between data points to find hidden relationships that the human eye would struggle to find. The LSTM model also keeps the memory of previous computations, which assists in narrowing the accuracy of the prediction of a class [67].

One aim of this research was to improve upon the accuracy of predicting whether segments of movement between two people are coordinated or not using machine learning techniques. This could be applied in a single instance between two people with a small training dataset, so as to make this analysis more accessible for grass-roots sports coaches who don't have access to large amounts of data. This research also aims to show whether an IMU-based dataset is appropriate to answer the research question: can coordination between people be accurately quantified?

4.2 Materials & Methods

Ethics

The Medical Sciences Interdivisional Research Ethics Committee (IDREC) reviewed and approved the protocol for this study, which can be found under the reference: R92954/RE002.

The Coordination Game

The Coordination Game, as explained in detail in Chapter 3, was used in this study.

Xsens DOT sensors (IMUs)

The IMUs used in this study are Xsens DOT sensors (Movella, Henderson, NV, USA). Within them are accelerometers, gyroscopes, and magnetometers collecting accelerations, angular velocities, and magnetic fields, respectively. The Xsens DOT sensors utilize the Xsens Kalman Filter core (XKFCore) algorithm for sensor fusion. This algorithm filters and processes the raw data before it is outputted. The initial collection of 5 of the sets of data used Euler angles for the orientation (magnetometer) measurements. These were converted to quaternions to avoid gimbal lock and loss of data [62]. Each participant wore one IMU on their chest and one IMU on their forehead using comfortable straps.

Classification Analysis

The Classification Learner in MATLAB (R2022a) has a host of different classifiers which were tested for this project, and the most successful and relevant classifiers were shown to be the Support Vector Machine (SVM) Kernel and K-nearest-neighbours (KNN). The SVM is commonly utilized in labelling two different classes. Given this study works with a binary system of coordinated and uncoordinated, this methodology suits very well.

The Kernel in SVMs allows for linear methodology to be applied to non-

linear data. K-nearest-neighbours (KNN) is one of the simplest classification techniques. KNN classifies nodes based on the nearest neighbouring nodes. The Classification Learner also allows for fine, medium, and coarse classification, which can help with over and underfitting of the dataset. The coarse KNN was utilized for this study to help with overfitting.

Leave-one-out cross validation was utilized in this study, with a dataset of $n = 10$. The inputs were 9 training sets, and 1 testing set, with 10 dimensions of data per participant set. These 10 dimensions were: 3 dimensions of acceleration, 4 dimensions of orientation (in quaternions), and 3 dimensions of angular velocity. The outputs were training validation and testing accuracy scores, as well as a confusion matrix.

Long Short Term Memory (LSTM)

Time series analysis seems useful to this study because the dataset relies what kinds of movements occur over time. Long Short Term Memory is a time series analysis method which uses hidden layers to manipulate minute relationships between nodes. The parameters of this process are: hidden units (layers), maximum epochs (the amount of times the data is fully run through the LSTM machine), learning rate (the width of the step between nodes), number of classes (coordinated and uncoordinated), window width (the size of the window passing over the data), and offset (the size of the difference between chunks of data). These values were optimised and ended up being the following:

- Hidden Units: 2

- Maximum Epochs: 50
- Learning Rate: 0.001
- Number of Classes: 2
- Window Width: 300
- Offset: $\frac{WindowWidth}{9}$

The Window Width is 300 because the data was collected at 60Hz, so one full second of data is 60 samples. Thus, the Window Width is 300, or, 5 seconds long. This length of data was found to be the optimal length through trial and error. Given the length of coordinated and uncoordinated sections were around 50 seconds and 30 seconds long, respectively, and the human response time to seeing movement and copying it being around 0.2-0.3 seconds [63], using chunks of 5 seconds worth of data to attempt to find the most accurate binary decision making is understandable.

The input for the LSTM is the same 10 dimensions of data from each participant as for the classifiers. The output is a training accuracy graph over each iteration the LSTM runs through, a loss function, a training validation accuracy, and a testing accuracy.

4.3 Results

SVM Kernel

The confusion matrix from training and testing this dataset with the SVM kernel is shown in Figure 4.1. The training validation accuracy score was

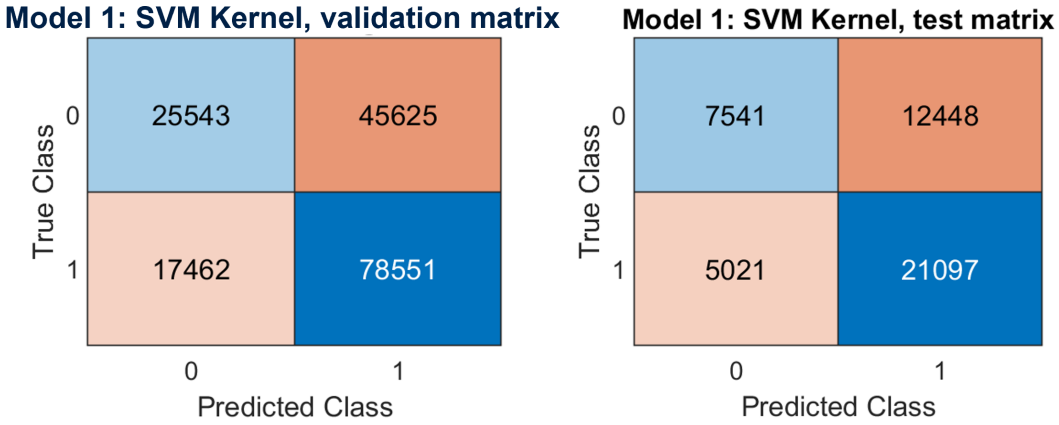


Figure 4.1: The SVM Kernel training validation matrix (left) and testing matrix (right). The training validation accuracy was 62.3% and the testing accuracy was 62.1%.

calculated to be 62.3%, and the testing accuracy score was calculated to be 62.1%. These scores are very similar, which shows that there is little overfitting occurring with this methodology.

KNN

In Figure 4.2, the confusion matrix from both the training and testing data are shown. The training validation accuracy score and the testing accuracy score was 80.6% and 55.6%, respectively. This large drop in accuracy might be due to overfitting occurring during the training of this model.

LSTM

The testing validation accuracy achieved with the LSTM was 63.4%. The loss function shows little overfitting (Fig. 4.3).

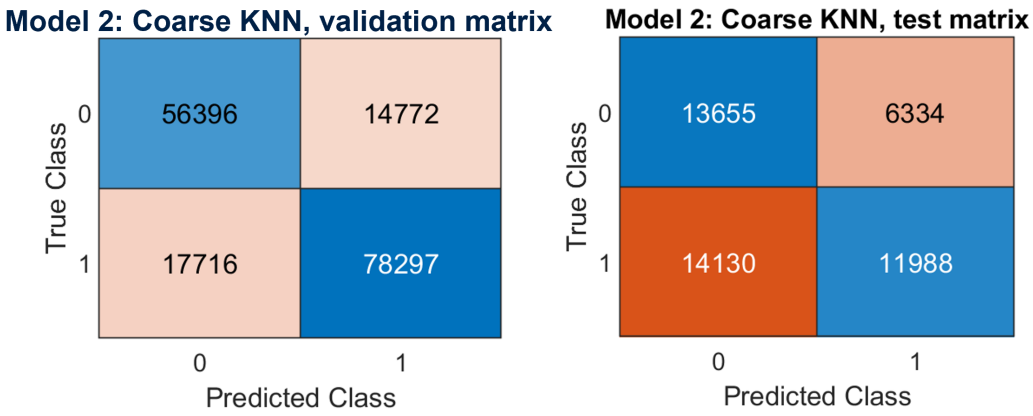


Figure 4.2: The coarse KNN training validation matrix (left) and testing matrix (right). The training validation accuracy was 80.6% and the testing accuracy was 55.6%.

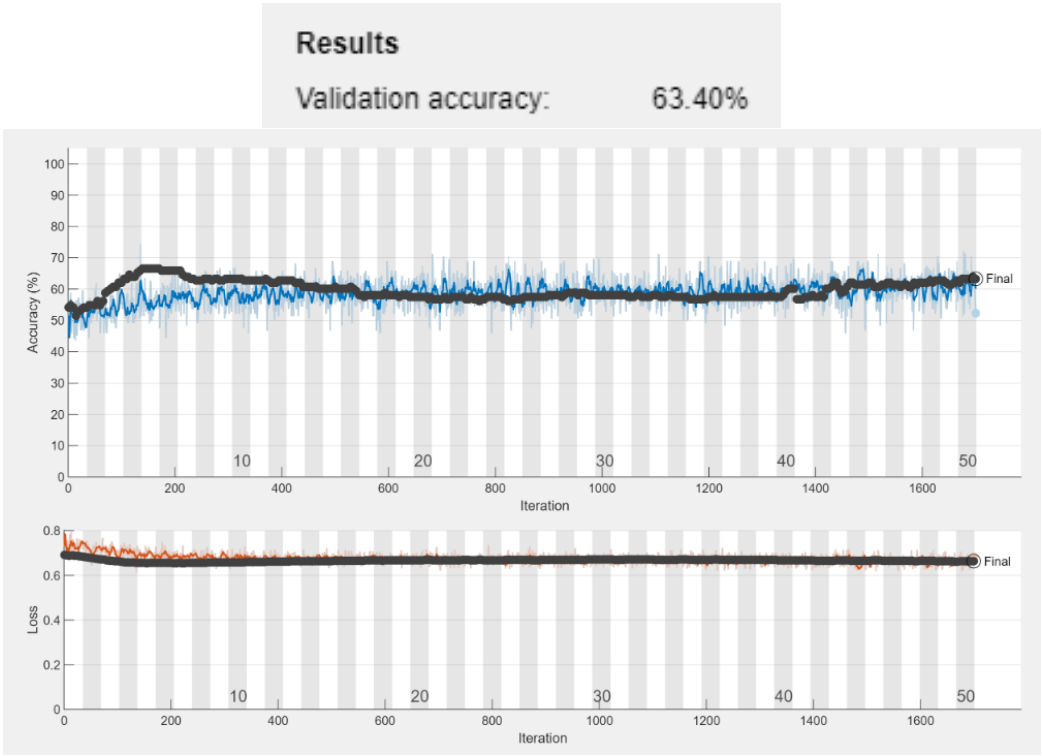


Figure 4.3: Results from the LSTM model, including the loss function.

4.4 Discussion

All classification methodologies performed similarly. It is important to note that an accuracy score of 50% is random chance of selecting the correct class between two classes. The testing validation accuracy scores for all three methodologies were 62.1% (SVM kernel), 55.6% (coarse KNN), and 63.4% (LSTM). These scores are too close to random chance (50%) to make any accurate decisions on coordinated and uncoordinated segments of movement.

The SVM kernel obtained very similar training and testing accuracy scores (62.3% and 62.1%, respectively). This means that there was little to no overfitting occurring with this particular methodology. However, these are still low-accuracy scores. Values closer to 80% were expected, given the possibility for accuracy with the simple correlation by association methodology from Chapter 3. There were 2 distinct ranges of correlation coefficients. If a segment of movement achieved a correlation coefficient (r) between $0.15 - 0.23$, that segment of movement could most likely be classified as uncoordinated. If r fell between $0.30 - 0.54$, then the segment of movement could most likely be classified as coordinated. Again, these are very distinct ranges. It is surprising that the classifiers which are able to compute complex relationships within data are unable to classify this data with high accuracy.

Similarly low accuracy scores were achieved with the coarse KNN and LSTM models. The coarse KNN achieved the lowest accuracy score of the three models presented here, with a score of 55.6%.

A limitation of this study is that the data is not equal parts (50-50)

coordinated and uncoordinated tasks. This difference in the number of each type of task was not accounted for in the analysis.

4.5 Conclusions

A maximum of 63.4% accuracy (LSTM) was obtained from the methodologies tested in this chapter. This methodology needs further testing, as the capacity of each method was not fully explored. Different parameters or inclusions of other data might prove fruitful in identifying coordination between people.

Chapter 5

Discussion and Future Work

In this thesis, an over-arching definition and a novel reference dataset have been provided, along with preliminary analysis. First, a preliminary research question was investigated: can coordination be used to predict injury? No generally applicable definition of the term "coordination" was found to be agreed-upon in any field, and no common methodology was described in any study regarding coordination and the utilisation of it to predict injury. The rift in the research of coordination and sports medicine was further explored as the main investigation in this thesis. A definition for the term "coordination" was created to help close the rift:

Coordination: two (or more) factors working together during a functional task.

This definition was applied and tested in the main investigation. My proposed Coordination Game utilizes this broad definition, and is designed to keep in mind that the current literature uses many different coordination

measurement methods and terms. This Coordination Game is able to capture any work discussing any kind of coordination, be it "motor control" or "technical-tactical coordination".

As previously mentioned in Chapter 1, this thesis began with the research question: can coordination be used to predict injury? However, once the systematic literature review was completed, it was apparent that the existing research in coordination needed a foundation in order to explore further concepts surrounding coordination, such as coordination between people. Thus, this thesis' main objective became: define coordination for between bodies, and develop a measurement method for group coordination. Once this definition and measurement method for group coordination are satisfactorily developed, research in group coordination can move forwards into answering research questions such as the initial exploration in this thesis: to find coordination's role in injury prediction.

The work in Chapters 3 and 4 should help lay the foundations for group coordination research. The use of correlation coefficients and classification methodologies could be used in future work involving injury prediction. If coordination between teammates is poor, perhaps the incident of injury becomes more common. Future work could utilize the Coordination Game to measure a baseline of correlation coefficients between teammates, and the number of injury incidences over the course of multiple seasons could be catalogued. Then, if the coordination between teammates becomes better (seen with higher correlation coefficients), stays the same (follows baseline), or becomes worse (lower correlation coefficients) over the seasons, some conclusions could be drawn with the number of catalogued injury incidences in

mind.

Following a literature deep-dive, a spontaneous group coordination study investigating pedestrians crossing streets was used as inspiration for the development of the Coordination Game. This game is a bare-bones and accessible test for coordination between people. Inertial measurement units, which are cheaper than video camera setups and GPS units, an open field of dimensions 10 by 20 meters, and two participants are all that is necessary to use this methodology. Coordinated movements are captured in the Coordination Game by giving two functional tasks to the participants (to Lead and to Follow), whereas uncoordinated movements are captured by not giving any functional tasks to either participant and asking that they ignore the other participant. This methodology follows the qualitative definition created post-literature-analysis.

To validate the Coordination Game as a generally applicable test for coordination, the simplest methodology was first utilized alongside it: correlation by association. Pearson correlation coefficients were calculated for each coordinated and uncoordinated segment of movement (of which there were equal amounts, $n, m = 66$ segments of each class). Ranges of correlation coefficients for coordinated and uncoordinated segments were found across all data: $[0.15 - 0.23]$ implies uncoordinated movements and $[0.3 - 0.54]$ implies coordinated movements. Along with these distinct ranges, a p-value of < 0.001 was obtained, supporting the significance of these differences in coordination and uncoordinated correlation coefficients.

These ranges were found by measuring multiple sets of participants. Amongst the individual tests, there are some segments of uncoordinated movements

that come quite close in correlation value to coordinated movements. This individual analysis was further investigated using more complex methodology: machine learning classifiers. It is valuable to have the obtained ranges of correlation coefficients, but it would be useful to be able to identify coordinated and uncoordinated segments on every individual basis (per each participant, alone).

Duarte et al 2012 studied coordination between people under the term "interpersonal synchrony" using correlation coefficients. This study used a different metric and measured their version of coordination with video analysis alone. Their correlation coefficients seemed to be in much higher ranges in comparison to the Coordination Game's [68], but the exact correlation coefficients are not provided. This study is an example of a related methodology to the Coordination Game, however it cannot be compared due to the differences in metric and evaluation. The provided definition and quantification of coordination via the Coordination Game is currently the coordination-between-people field of research's first of its kind. Hopefully in the near future, the ranges implying coordinated and uncoordinated movement can be tested an validated in different scenarios.

Different machine learning classifiers were tested with similar data. The classifiers included were Support Vector Machine (SVM) Kernel, coarse K-nearest neighbors, and long short-term memory (LSTM) models. The parameters and dimensions of data tested garnered testing accuracy scores of 62.1%, 55.6%, and 63.4%, respectively. The best-performing classifier was the LSTM model, with the 63.4% testing accuracy score. Given that the parameters of the LSTM can be developed and tested further, this testing

accuracy score could definitely be improved upon. However, initially, the LSTM has proven itself as the best method so far for classifying coordination.

Limitations of this thesis must be addressed. Within Chapter 2, important articles may have been missed if they did not use the terms "synchrony" or "coordination". These missing articles might have provided other, different terms and definitions for coordination. This limitation could be improved upon if literature investigating coordination used a common terminology or a common definition, neither of which exists yet. Hopefully, the definition provided in this thesis can be appropriated by the many fields that research coordination.

Within Chapter 3, only 14 participants' data were able to be analysed. This means there were only 7 viable tests. More participants were desired for further significance analysis, especially since there were multiple individual tests that had not-so-dissimilar correlation coefficients between coordinated and non-coordinated movements. Another possible investigation could include specifying to the participants whether they should or should not be attempting to match each other's steps. Small bumps can be seen in the cross correlation figures (Figs. 3.3 and 3.4), which represent the amalgamation of consistent step cycles in each test. Perhaps if step cycles were synchronized, the calculated correlation coefficients would be different. Lastly, it should be noted that perhaps the correlation coefficients of uncoordinated segments and coordinated segments will always be near in value. Some individuals might just have poor coordination, and their coordinated and non-coordinated values will always be similar. Also, in the random walking segment of the

Coordination Game, there will always be certain lengths of time where the two participants, despite not having any instruction to follow each other, will accidentally be moving in the same direction or at the same acceleration. These factors are important to keep in mind when gauging the accuracy of utilizing correlation by association to identify coordination.

Within Chapter 4, multiple classifier models were tested. It is worth noting that there are many existing classification methodologies, some of which were not utilized in this study. Aside from this, the parameters of the LSTM were majorly investigated; however, there still might be more optimal values for those parameters. The classifiers included in this study showed the least amount of overfitting. However, perhaps the dimensions of data (3 axes of accelerations, 3 axes of angular velocities, and 4 axes of orientation) were not optimal. Feature analysis would be a useful next step in identifying important dimensions of data, which then might help improve over- and under-fitting and classification accuracy.

When the limitations listed above are overcome, the continuation of this research can be applied to helping any population that finds measuring coordination between people useful. This can be in a sports environment between teammates and opponents, or in a crowded room of at-risk individuals, or, as mentioned in the study that inspired the Coordination Game [15], in the street as pedestrians cross in front of cars. The impact of this research is wide-reaching, and already on the way to affecting how research is carried out in this subject.

Future work that is needed to continue the investigation of this thesis includes more data and more literature. The correlation coefficient method-

ology should be next applied to the real sporting environment that inspired the Coordination Game: man-on-man defense during pass routes practice in American football. This application will help evolve the use of the methodologies discussed in this thesis for use by coaches to improve their athlete's performance via the study of the coordination between their players. More complex tools need to be tested for their ability to accurately quantify coordination between players, such as GPS units and multi-camera video analysis. Larger datasets, with more participants and more scenarios per participant, will assist in investigating and improving the use of machine learning methodologies to successfully classify coordinated and uncoordinated segments of movement. Finally, the application of this work to injury prediction must be investigated. This project began with the research question: can coordination be used to predict injury between people? Now that the foundation of research involving coordination between people has been laid, the definitions and methodologies can be used to investigate coordination's role in injury prediction.

This thesis opens the door to start using common language (terminology *and* definition) and common methodology (the Coordination Game), which should provide assistance in furthering this line of research. The results throughout this thesis show continuous support for the hypotheses listed in Section 1.2. Firstly, that coordination between people can be accurately measured. Secondly, that IMUs and simple correlation analysis can quantify coordination between people. Lastly, that classification analysis provides a step further in quantifying coordination between people. This thesis concludes that coordination between people can be quantified, and is worth

further research.

Appendix

Supplemental Table 1

Authors	Year published
Chumanov ES	2007
Rommers N	2020
Schuermans J	2017
Tojima M, Torii S.	2018
Schuermans J	2017
Vrbanic, TSL	2007
Tojima M, Torii S.	2017
Schuermans J	2016
McLean, SG	2005
Hewett TE	2005
Alshehri MA	2024
Park YG	2023
Butowicz CM	2022
Gauthier M	2022
Cui X	2022
Chmura P	2022
Desai GA	2022
Bussey MD	2023
Wang S, Wang Y.	2022
Mercado-Palomino E	2021
Sargent SD	2024
Versloot, Olav	2023
Alonzo, Corrie J.	2022
Samaan, Michael A.	2022
de Sire, Alessandro	2021
Gogoi, Hemantajit	2021
Sutanto D	2025
Xu X	2024
Chen Y	2024
Kikuchi K	2024
Yang K, Li B.	2024
Li H.	2025
Anandhi D.	2024

Title

The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting

A Machine Learning Approach to Assess Injury Risk in Elite Youth Football Players

Deviating running kinematics and hamstring injury susceptibility in male soccer players: Cause or consequence?

COMPARISON OF LUMBOPELVIC RHYTHM AMONG ADOLESCENT SOCCER PLAYERS WITH AND WITHOUT LOW BACK PAIN

Prone Hip Extension Muscle Recruitment is Associated with Hamstring Injury Risk in Amateur Soccer

Balance index score as a predictive factor for lower sports results or anterior cruciate ligament knee injuries in Croatian female athletes - Pr

Changes in lumbopelvic rhythm during trunk extension in adolescent soccer players

Susceptibility to Hamstring Injuries in Soccer: A Prospective Study Using Muscle Functional Magnetic Resonance Imaging

Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury

Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female at

Poor lumbar spine coordination in acute low back pain predicts persistent long-term pain and disability

Relationships between Clinical Status and Gait Parameters in Ankylosing Spondylitis

Low back pain influences trunk-lower limb joint coordination and balance control during standing in persons with lower limb loss

Subjective knee apprehension is not associated to physical parameters 6-12 months after anterior cruciate ligament reconstruction

Biomechanical Analysis on Skilled Badminton Players during Take-Off Phase in Forehand Overhead Strokes: A Pilot Study

Physical Performance Indicators and Team Success in the German Soccer League

Bilateral differences in coordination variability among injured and uninjured runners: A prospective study

Anticipatory head control mechanisms in response to impact perturbations: An investigation of club rugby players with and without a histor

Musculoskeletal Model for Assessing Firefighters' Internal Forces and Occupational Musculoskeletal Disorders During Self-Contained Breat

The influence of limb role, direction of movement and limb dominance on movement strategies during block jump-landings in volleyball

Self-reported Measures of Function Compared to Lower Limb Motor Performance in People With and Without Imaging Evidence of Unilatera

Can motor proficiency testing predict sports injuries and sports-induced bleeds in people with haemophilia?

High Prevalence of Abnormal General Movements in Hospitalized Very Low Birth Weight Infants

Hip–Knee Joint Coordination Patterns are Associated With Patellofemoral Joint Cartilage Composition in Patients With Anterior Cruciate Lig

Electromyographic assessment of anterior cruciate ligament injury risk in male tennis players: Which role for visual input? a proof-of-conce

A statistical model for prediction of lower limb injury of active sportsperson

Difference in movement coordination and variability during Five-Repetition Sit-to-Stand between people with and without Chronic Low back

Coordination Between Respiration and Swallowing in Patients With Dysphagia After Cervical Spinal Cord Injury: An Observational Case-Cor

Attentional network deficits in patients with migraine: behavioral and electrophysiological evidence

Difficulties in perceptual-motor coordination of reaching behavior in children with autism spectrum disorder

Impact of lower limb alignment abnormality (physiologic knee valgus) on the functional recovery outcome of athletes with meniscal injuries

A Novel Integration of Bodily-Kinesthetic Intelligence (BKI) and Feature Mining Methodology: Applications in Fall Risk Assessments

Predict the musculoskeletal injuries in young skaters using Functional Movement Screen (FMS™)

Authors	Year	Number of participants	Sex of participants (male - M, female - F)
Chumanov ES	2007	19	14 M and 5 F
Rommers N	2020	734	All M
Schuermans J	2017	30	All M
Tojima M, Torii S.	2018	109	All M
Schuermans J	2017	51	All M
Vrbanic, TSL	2007	52	All F
Tojima M, Torii S.	2017	63	All M
Schuermans J	2016	54	All M
McLean, SG	2005	20	10 M and 10 F
Hewett TE	2005	205	All F (specifically to study a difference in sex)
Alshehri MA	2024	94	49 M and 45 F
Park YG	2023	258	198 M and 60 F
Butowicz CM	2022	40	24 M and 16 F
Gauthier M	2022	303	212 M and 91 F
Cui X	2022	6	All M
Chmura P	2022	unknown	unknown
Desai GA	2022	31	11 M and 20 F
Bussey MD	2023	51	All M
Wang S, Wang Y.	2022	12	All M
Mercado-Palomino E	2021	14	All F
Sargent SD	2024	45	29 M and 16 F
Versloot, Olav	2023	125	unknown
Alonzo, Corrie J.	2022	121	69 M and 52 F
Samaan, Michael A.	2022	35	19 M and 16 F
de Sire, Alessandro	2021	20	All M
Gogoi, Hemantajit	2021	75	All M
Sutanto D	2025	66	35 M and 31 F
Xu X	2024	95	75 M and 20 F
Chen Y	2024	86	43 M and 43 F
Kikuchi K	2024	26	20 M and 6 F
Yang K, Li B.	2024	118	85 M and 33 F
Li H.	2025	48	25 M and 23 F
Anandhi D.	2024	64	43 M and 21 F

Authors	Year	Age of participants
Chumanov ES	2007	13-26 years, but averaged at 21 (males) and 20 (females)
Rommers N	2020	"under 10 yr (U10) up to the under 15 yr (U15)" p. 1746, "mean age, 11.7 ± 1.7 y
Schuermans J	2017	24.7 (±3.4) years
Tojima M, Torii S.	2018	13.1 ± 0.9 years
Schuermans J	2017	24 ± 3.5 years
Vrbanic, TSL	2007	18.4±0.5 years
Tojima M, Torii S.	2017	12.7±0.6 years
Schuermans J	2016	23 ±5 years
McLean, SG	2005	20.2 (±1.9) M, 21.1 (±3.0) F years
Hewett TE	2005	15.8 ± 1.0 (injured) vs 16.1 ± 1.7 years (uninjured)
Alshehri MA	2024	29 ± 7.8 years
Park YG	2023	42.2 ± 12.3 years
Butowicz CM	2022	34.7 ± 8.6 years
Gauthier M	2022	27 ± 8 years
Cui X	2022	25.0 ± 0.9 years
Chmura P	2022	unknown
Desai GA	2022	31.8 ± 10.4 years
Bussey MD	2023	20.6 ± 1.5 years
Wang S, Wang Y.	2022	23.1 ± 2.1 years
Mercado-Palomino E	2021	20.4 ± 2.2 years
Sargent SD	2024	52.7 ± 15.8 years
Versloot, Olav	2023	25 ± 12 years
Alonzo, Corrie J.	2022	28.3 ± 2.6 **WEEKS**
Samaan, Michael A.	2022	29.2 ± 8.3 years
de Sire, Alessandro	2021	20.3 ± 4.8 years
Gogoi, Hemantajit	2021	18.31 ± 1 years
Sutanto D	2025	31.5 ± 9.1 years
Xu X	2024	49.8 ± 11 years
Chen Y	2024	29.8 ± 7.2 years
Kikuchi K	2024	9.7 ± 1.5 years
Yang K, Li B.	2024	21.7 ± 2.2 years
Li H.	2025	74.1 ± 6.5 years
Anandhi D.	2024	11.1 ± 2.8 years

Authors	Year	Injury location	Sports mention
Chumanov ES	2007	Hamstring	Yes
Rommers N	2020	Any overuse or acute football injury	Yes
Schuermans J	2017	Hamstring	Yes
Tojima M, Torii S.	2018	Lower back	Yes
Schuermans J	2017	Hamstring	Yes
Vrbanic, TSL	2007	ACL	Yes
Tojima M, Torii S.	2017	Lower back	Yes
Schuermans J	2016	Hamstring	Yes
McLean, SG	2005	ACL	Yes
Hewett TE	2005	ACL	Yes
Alshehri MA	2024	Lower back	Yes
Park YG	2023	Spine	No
Butowicz CM	2022	Lower back and unilateral limb loss	Yes
Gauthier M	2022	ACL	Yes
Cui X	2022	Lower extremities	Yes
Chmura P	2022	Running injuries	Yes
Desai GA	2022	General (hip, knee, and foot were most common)	Yes
Bussey MD	2023	Neck	Yes
Wang S, Wang Y.	2022	Musculoskeletal injuries	No
Mercado-Palomino E	2021	Lower limb	Yes
Sargent SD	2024	Spine	No
Versloot, Olav	2023	General	Yes
Alonzo, Corrie J.	2022	General	No
Samaan, Michael A.	2022	ACL	No
de Sire, Alessandro	2021	ACL	Yes
Gogoi, Hemantajit	2021	Lower limb	Yes
Sutanto D	2025	Lower back	No
Xu X	2024	Throat	No
Chen Y	2024	Head	No
Kikuchi K	2024	Hand	No
Yang K, Li B.	2024	Lower limb	Yes
Li H.	2025	General (fall risk)	No
Anandhi D.	2024	Musculoskeletal	Yes

Authors	Year	Sport
Chumanov ES	2007	Running
Rommers N	2020	Soccer
Schuermans J	2017	Soccer
Tojima M, Torii S.	2018	Soccer
Schuermans J	2017	Soccer
Vrbanic, TSL	2007	Handball and volleyball
Tojima M, Torii S.	2017	Soccer
Schuermans J	2016	Soccer
McLean, SG	2005	Basketball
Hewett TE	2005	Soccer, basketball, and volleyball
Alshehri MA	2024	General
Park YG	2023	N/A
Butowicz CM	2022	General
Gauthier M	2022	"pivoting and jumping sports"
Cui X	2022	Badminton
Chmura P	2022	Soccer
Desai GA	2022	Running
Bussey MD	2023	Rugby
Wang S, Wang Y.	2022	N/A
Mercado-Palomino E	2021	Volleyball
Sargent SD	2024	N/A
Versloot, Olav	2023	General
Alonzo, Corrie J.	2022	N/A
Samaan, Michael A.	2022	N/A
de Sire, Alessandro	2021	Tennis
Gogoi, Hemantajit	2021	Running
Sutanto D	2025	N/A
Xu X	2024	N/A
Chen Y	2024	N/A
Kikuchi K	2024	N/A
Yang K, Li B.	2024	Weightlifting, athletics, team sport
Li H.	2025	N/A
Anandhi D.	2024	Skating

Authors	Year	Coordination term used
Chumanov ES	2007	Neuromuscular coordination
Rommers N	2020	Motor coordination
Schuermans J	2017	Running coordination
Tojima M, Torii S.	2018	Hip-spine coordination, or lumbopelvic rhythm (LPR)
Schuermans J	2017	Neuromuscular coordination, or lumbo-pelvic function
Vrbanic, TSL	2007	Neuromuscular control
Tojima M, Torii S.	2017	Hip-spine coordination, or lumbopelvic rhythm (LPR)
Schuermans J	2016	Neuromuscular coordination/intermuscular coordination
McLean, SG	2005	Neuromuscular control.
Hewett TE	2005	Neuromuscular control.
Alshehri MA	2024	Hip-to-spine coordination
Park YG	2023	Coordination
Butowicz CM	2022	Trunk-lower limb joint coordination
Gauthier M	2022	Coordination
Cui X	2022	Joint coordination
Chmura P	2022	Technical-tactical coordination
Desai GA	2022	Coordination variability
Bussey MD	2023	Hand-eye coordination
Wang S, Wang Y.	2022	Coordinated movement
Mercado-Palomino E	2021	Coordination
Sargent SD	2024	Sensorimotor control
Versloot, Olav	2023	Motor proficiency
Alonzo, Corrie J.	2022	General movements
Samaan, Michael A.	2022	Hip-knee joint coordination
de Sire, Alessandro	2021	Muscle coactivation
Gogoi, Hemantajit	2021	Gait
Sutanto D	2025	Movement coordination
Xu X	2024	Coordination of respiration and swallowing
Chen Y	2024	Executive control
Kikuchi K	2024	Perceptual-motor coordination
Yang K, Li B.	2024	Motor functional performance
Li H.	2025	Motor skills
Anandhi D.	2024	Coordination

Authors	Year	Coordination definition provided?
Chumanov ES	2007	No
Rommers N	2020	Yes
Schuermans J	2017	Yes
Tojima M, Torii S.	2018	Yes
Schuermans J	2017	Yes
Vrbanic, TSL	2007	Yes
Tojima M, Torii S.	2017	No
Schuermans J	2016	No
McLean, SG	2005	No
Hewett TE	2005	No
Alshehri MA	2024	Yes
Park YG	2023	No
Butowicz CM	2022	Yes
Gauthier M	2022	No
Cui X	2022	No
Chmura P	2022	No
Desai GA	2022	Yes
Bussey MD	2023	No
Wang S, Wang Y.	2022	No
Mercado-Palomino E	2021	No
Sargent SD	2024	No
Versloot, Olav	2023	No
Alonzo, Corrie J.	2022	Yes
Samaan, Michael A.	2022	No
de Sire, Alessandro	2021	No
Gogoi, Hemantajit	2021	No
Sutanto D	2025	No
Xu X	2024	No
Chen Y	2024	Yes
Kikuchi K	2024	Yes
Yang K, Li B.	2024	No
Li H.	2025	Yes
Anandhi D.	2024	No

Authors	Year	Coordination definition
Chumanov ES	2007	
Rommers N	2020	flexibility of the lower back and posterior chain, endurance, three different strength measures, abdominal strength, speed, and agility. p.1746
Schuermans J	2017	"Coordination" is a factor of lumbopelvic control. They define "core stability", in their terms, in "fairly broad functional interpretation" p.271
Tojima M, Torii S.	2018	"the concurrent movement of the hip joint and lumbar spine (LS) as they contribute to locomotor function of the lower limbs" p.172.
Schuermans J	2017	"neuromuscular coordination, assessed by means of the PHE exercise" p.698
Vrbanic, TSL	2007	"Normal balance and balance during sports activities require proper neuromuscular control" p.253
Tojima M, Torii S.	2017	
Schuermans J	2016	
McLean, SG	2005	
Hewett TE	2005	
Alshehri MA	2024	"Movement of the spine with the seat"
Park YG	2023	
Butowicz CM	2022	"joint coordination patterns lie on a continuum of potential solutions for balance stabilization"
Gauthier M	2022	
Cui X	2022	
Chmura P	2022	
Desai GA	2022	"Variability in relative joint and/or segment motions over the gait cycle"
Bussey MD	2023	
Wang S, Wang Y.	2022	
Mercado-Palomino E	2021	
Sargent SD	2024	
Versloot, Olav	2023	
Alonzo, Corrie J.	2022	
Samaan, Michael A.	2022	
de Sire, Alessandro	2021	
Gogoi, Hemantajit	2021	
Sutanto D	2025	
Xu X	2024	
Chen Y	2024	"These networks are crucial for detecting, selecting, and organizing internal and external information, thereby enabling adaptive behavior"
Kikuchi K	2024	"the utilization of perceptually derived information (e.g., from vision or touch) in the control of ongoing movements (APA Dictionary of Psychol
Yang K, Li B.	2024	
Li H.	2025	the body's ability to maintain balance
Anandhi D.	2024	

Authors	Year	Coordination term measurement method
Chumanov ES	2007	Whole body kinematics using reflective markers, and muscle stress information from EMG surface electrodes
Rommers N	2020	"three subtest short version of the Körperkoordinationstest für Kinder (KTK3)" "Football-specific motor coordination was tested using the Ghent University dribbling
Schuermans J	2017	3D kinematics. Sprinting trials.
Tojima M, Torii S.	2018	3D motion analysis, trunk extension" p.173
Schuermans J	2017	The Prone Hip Extension (PHE)
Vrbanic, TSL	2007	Balance index score (BIS) measurement
Tojima M, Torii S.	2017	3D motion analysis. Measured lumbar motion with the 3D motion analysis system. Trunk extension was measured using hip ROM.
Schuermans J	2016	Muscle functional magnetic resonance imaging (mfMRI). "a strenuous eccentric hamstring exercise between scans" p.1278
McLean, SG	2005	"...right (contact) leg during the execution of three different sports movements" p.356
Hewett TE	2005	3D biomechanical analyses. "Knee joint flexion-extension and adduction-abduction were quantified for each subject over a series of drop vertical jump (DVJ) trials"
Alshehri MA	2024	Using an unstable sitting paradigm, sitting upright "as quietly as possible"
Park YG	2023	Phase coordination index (PCI) and gait analysis (walking on a treadmill)
Butowicz CM	2022	Standing still with their eyes closed or open
Gauthier M	2022	Triple hop test and side hop test
Cui X	2022	Footwork and overhead swing
Chmura P	2022	Soccer match
Desai GA	2022	Running trials (had to hit a certain speed), with gait analysis
Bussey MD	2023	Eyes closed or open pendulum swinging at their face while they stand still
Wang S, Wang Y.	2022	Running with a heavy load on their back
Mercado-Palomino E	2021	Jump-landings
Sargent SD	2024	Fitt's motor control task
Versloot, Olav	2023	Bruininks-Oseretsky Test 2 (BOT-2)
Alonzo, Corrie J.	2022	GM Assessment
Samaan, Michael A.	2022	Gait trials walking on force plates
de Sire, Alessandro	2021	Drop landing test
Gogoi, Hemantajit	2021	Walking on a treadmill
Sutanto D	2025	"Mean absolute relative phase (MARP) calculated from mean of the absolute CRP curve quantifies movement coordination"
Xu X	2024	"the parameters of coordination between respiration and swallowing include respiratory pattern, SAD and others"
Chen Y	2024	"ANT (i.e., the Attentional Networks Test for Interactions and Vigilance–Executive and Arousal Components, ANTI-Vea" and EEG measurements
Kikuchi K	2024	Moving a marble to a target with dominant hand, through or over obstacles
Yang K, Li B.	2024	ROM, VAS, IKDC, FPT
Li H.	2025	Walking test
Anandhi D.	2024	Rotary stability test

Authors	Year	Does coordination predict injury?	D&B 1	D&B 2	D&B 3	D&B 4	D&B 5
Chumanov ES	2007	Yes	Yes	Yes	Yes	Yes	Yes
Rommers N	2020	Yes	Yes	Yes	Yes	Yes	Yes
Schuermans J	2017	Yes	Yes	Yes	Yes	Yes	No
Tojima M, Torii S.	2018	Yes	Yes	Yes	Yes	Yes	Yes
Schuermans J	2017	Yes	Yes	Yes	Yes	Yes	Yes
Vrbanic, TSL	2007	Yes	Yes	Yes	Yes	Yes	Yes
Tojima M, Torii S.	2017	Yes	Yes	Yes	Yes	Yes	Yes
Schuermans J	2016	Yes	Yes	Yes	Yes	Yes	Yes
McLean, SG	2005	Yes	Yes	Yes	Yes	Yes	Yes
Hewett TE	2005	Yes	Yes	Yes	Yes	Yes	Yes
Alshehri MA	2024	No	Yes	Yes	Yes	Yes	Yes
Park YG	2023	Yes	Yes	Yes	Yes	Yes	No
Butowicz CM	2022	Yes	Yes	Yes	Yes	Yes	Yes
Gauthier M	2022	No	Yes	Yes	Yes	Yes	Yes
Cui X	2022	Yes	Yes	Yes	Yes	Yes	Yes
Chmura P	2022	Yes	Yes	Yes	No	Yes	No
Desai GA	2022	Inconclusive	Yes	Yes	Yes	Yes	Yes
Bussey MD	2023	Yes	Yes	Yes	Yes	Yes	Yes
Wang S, Wang Y.	2022	Yes	Yes	Yes	Yes	Yes	Yes
Mercado-Palomino E	2021	Yes	Yes	Yes	Yes	Yes	No
Sargent SD	2024	Yes	Yes	Yes	Yes	Yes	Yes
Versloot, Olav	2023	No	Yes	Yes	Yes	Yes	Yes
Alonzo, Corrie J.	2022	Yes	Yes	Yes	Yes	Yes	Yes
Samaan, Michael A.	2022	Yes	Yes	Yes	Yes	Yes	Yes
de Sire, Alessandro	2021	Yes	Yes	Yes	Yes	No	Yes
Gogoi, Hemantajit	2021	Yes	No	No	Yes	No	No
Sutanto D	2025	Yes, in some circumstances	Yes	Yes	Yes	Yes	Yes
Xu X	2024	Yes	Yes	Yes	Yes	No	Yes
Chen Y	2024	No	Yes	Yes	Yes	Yes	Yes
Kikuchi K	2024	Inconclusive	Yes	Yes	Yes	Yes	No
Yang K, Li B.	2024	Yes	Yes	Yes	Yes	Yes	Yes
Li H.	2025	Yes	Yes	Yes	Yes	No	Yes
Anandhi D.	2024	Yes	Yes	Yes	Yes	Yes	Yes

Authors	Year	D&B 6	D&B 7	D&B 8
Chumanov ES	2007	Yes	Unable to determine	No
Rommers N	2020	Yes	Unable to determine	No
Schuermans J	2017	No	Unable to determine	No
Tojima M, Torii S.	2018	Yes	Yes	No
Schuermans J	2017	Yes	Yes	No
Vrbanic, TSL	2007	Yes	Unable to determine	No
Tojima M, Torii S.	2017	Yes	Unable to determine	No
Schuermans J	2016	Yes	Unable to determine	No
McLean, SG	2005	Yes	Unable to determine	No
Hewett TE	2005	Yes	Unable to determine	No
Alshehri MA	2024	Yes	Unable to determine	Unable to determine
Park YG	2023	Yes	Yes	Yes
Butowicz CM	2022	Yes	Yes	Unable to determine
Gauthier M	2022	Yes	Yes	Unable to determine
Cui X	2022	No	No	No
Chmura P	2022	No	Unable to determine	Unable to determine
Desai GA	2022	Yes	Unable to determine	Yes
Bussey MD	2023	Yes	Yes	Unable to determine
Wang S, Wang Y.	2022	No	Unable to determine	Unable to determine
Mercado-Palomino E	2021	Unable to determine	Unable to determine	Unable to determine
Sargent SD	2024	Yes	No	No
Versloot, Olav	2023	Yes	Yes	No
Alonzo, Corrie J.	2022	Yes	Yes	No
Samaan, Michael A.	2022	No	Yes	No
de Sire, Alessandro	2021	Yes	Unable to determine	No
Gogoi, Hemantajit	2021	Yes	Unable to determine	Unable to determine
Sutanto D	2025	Yes	Yes	Yes
Xu X	2024	Yes	Yes	Yes
Chen Y	2024	Yes	Yes	Yes
Kikuchi K	2024	Yes	Unable to determine	Unable to determine
Yang K, Li B.	2024	Yes	Yes	Unable to determine
Li H.	2025	Yes	Unable to determine	Unable to determine
Anandhi D.	2024	No	Yes	Yes

Authors	Year	D&B 9	D&B 10	D&B 11	D&B 12
Chumanov ES	2007	Yes	Yes	No	Unable to determine
Rommers N	2020	Yes	Yes	No	Yes
Schuermans J	2017	Yes	Yes	Yes	Yes
Tojima M, Torii S.	2018	Yes	Yes	Yes	Yes
Schuermans J	2017	Yes	Yes	Yes	Yes
Vrbanic, TSL	2007	Yes	Yes	Yes	Unable to determine
Tojima M, Torii S.	2017	Yes	Yes	Yes	Unable to determine
Schuermans J	2016	Yes	Yes	No	Yes
McLean, SG	2005	Yes	Yes	Yes	Unable to determine
Hewett TE	2005	Yes	Yes	No	No
Alshehri MA	2024	Yes	Yes	Unable to determine	Unable to determine
Park YG	2023	Yes	Yes	Yes	Yes
Butowicz CM	2022	Yes	Yes	No	Unable to determine
Gauthier M	2022	Yes	Yes	Yes	No
Cui X	2022	Yes	Yes	Yes	Unable to determine
Chmura P	2022	Yes	Yes	Yes	No
Desai GA	2022	Yes	Yes	Unable to determine	Unable to determine
Bussey MD	2023	Yes	Yes	Yes	No
Wang S, Wang Y.	2022	Yes	Yes	Unable to determine	Unable to determine
Mercado-Palomino E	2021	Unable to determine	Yes	Yes	Unable to determine
Sargent SD	2024	Yes	Yes	Yes	Yes
Versloot, Olav	2023	Yes	Yes	Yes	Yes
Alonzo, Corrie J.	2022	Yes	Yes	Yes	Yes
Samaan, Michael A.	2022	Yes	Yes	Yes	Unable to determine
de Sire, Alessandro	2021	Yes	Yes	Yes	Yes
Gogoi, Hemantajit	2021	No	No	Unable to determine	Unable to determine
Sutanto D	2025	Yes	Yes	No	Yes
Xu X	2024	Yes	Yes	Yes	Yes
Chen Y	2024	Yes	Yes	Yes	Unable to determine
Kikuchi K	2024	Yes	Yes	Unable to determine	Unable to determine
Yang K, Li B.	2024	Yes	Yes	Yes	Unable to determine
Li H.	2025	Yes	Yes	Unable to determine	Unable to determine
Anandhi D.	2024	Yes	Yes	Yes	Unable to determine

Authors	Year	D&B 13	D&B Score ?/13
Chumanov ES	2007	Yes	9
Rommers N	2020	Yes	10
Schuermans J	2017	Yes	9
Tojima M, Torii S.	2018	Yes	12
Schuermans J	2017	Yes	12
Vrbanic, TSL	2007	Yes	10
Tojima M, Torii S.	2017	Yes	10
Schuermans J	2016	Yes	10
McLean, SG	2005	Yes	10
Hewett TE	2005	Yes	9
Alshehri MA	2024	No	8
Park YG	2023	No	11
Butowicz CM	2022	Yes	10
Gauthier M	2022	No	10
Cui X	2022	Yes	9
Chmura P	2022	No	6
Desai GA	2022	Yes	10
Bussey MD	2023	Yes	11
Wang S, Wang Y.	2022	No	7
Mercado-Palomino E	2021	No	6
Sargent SD	2024	No	10
Versloot, Olav	2023	Yes	12
Alonzo, Corrie J.	2022	Yes	12
Samaan, Michael A.	2022	No	9
de Sire, Alessandro	2021	No	9
Gogoi, Hemantajit	2021	No	2
Sutanto D	2025	Yes	12
Xu X	2024	Yes	12
Chen Y	2024	No	11
Kikuchi K	2024	No	7
Yang K, Li B.	2024	No	10
Li H.	2025	No	7
Anandhi D.	2024	Yes	11

Supplemental Table 2

Downs & Black Modified Critical Appraisal Checklist for "Can coordination be used to predict injury? A Systematic Review." (1, 2)

Reporting
1. Is the hypothesis/aim/objective of the study clearly described?
2. Are the main outcomes to be measured clearly described in the Introduction or Methods section? If the main outcomes are first mentioned in the Results section, the question should be answered no.
3. Are the characteristics of the participants included in the study clearly described? In cohort studies and trials, inclusion and/or exclusion criteria should be given. In case-control studies, a case-definition and the source for controls should be given.
4. Are the distributions of principal confounders in each group of subjects to be compared clearly described? A list of principal confounders is provided.
5. Are the main findings of the study clearly described? Simple outcome data (including denominators and numerators) should be reported for all major findings so that the reader can check the major analyses and conclusions.
6. Does the study provide estimates of the random variability in the data for the main outcomes? In non normally distributed data the inter-quartile range of results should be reported. In normally distributed data the standard error, standard deviation or confidence intervals should be reported. If the distribution of the data is not described, it must be assumed that the estimates used were appropriate and the question should be answered yes.
External validity
7. Were the subjects asked to participate in the study representative of the entire population from which they were recruited? The study must identify the source population for patients and describe how the patients were selected. Patients would be representative if they comprised the entire source population, an unselected sample of consecutive patients, or a random sample. Random sampling is only feasible where a list of all members of the relevant population exists. Where a study does not report the proportion of the source population from which the patients are derived, the question should be answered as unable to determine.
8. Were those subjects who were prepared to participate representative of the entire population from which they were recruited? The proportion of those asked who agreed should be stated. Validation that the sample was representative would include demonstrating that the distribution of the main confounding factors was the same in the study sample and the source population.
Internal validity – bias
9. Were the statistical tests used to assess the main outcomes appropriate? The statistical techniques used must be appropriate to the data. For example nonparametric methods should be used for small sample sizes. Where little statistical analysis has been undertaken but where there is no evidence of bias, the question should be answered yes. If the distribution of the data (normal or not) is not described it must be assumed that the estimates used were appropriate and the question should be answered yes.
10. Were the main outcome measures used accurate (valid and reliable)? For studies where the outcome measures are clearly described, the question should be answered yes. For studies which refer to other work or that demonstrates the outcome measures are accurate, the question should be answered as yes.
Internal validity - confounding (selection bias)
11. Were the participants in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited from the same population? For example, patients for all comparison groups should be selected from the same hospital. The question should be answered unable to determine for cohort and case-control studies where there is no information concerning the source of patients included in the study.

12. Were study participants in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited over the same period of time? For a study which does not specify the time period over which patients were recruited, the question should be answered as unable to determine.
13. Was there adequate adjustment for confounding in the analyses from which the main findings were drawn? This question should be answered no for trials if: the main conclusions of the study were based on analyses of treatment rather than intention to treat; the distribution of known confounders in the different treatment groups was not described; or the distribution of known confounders differed between the treatment groups but was not taken into account in the analyses. In non-randomised studies if the effect of the main confounders was not investigated or confounding was demonstrated but no adjustment was made in the final analyses the question should be answered as no.
Score ?/13 Possible answers: yes, no, unable to determine. Scored: yes = 1, no = 0, unable to determine = 0.

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PRISMA 2020 for Abstracts Checklist

Section and Topic	Item #	Checklist item	Reported (Yes/No)
TITLE			
Title	1	Identify the report as a systematic review.	Yes
BACKGROUND			
Objectives	2	Provide an explicit statement of the main objective(s) or question(s) the review addresses.	Yes
METHODS			
Eligibility criteria	3	Specify the inclusion and exclusion criteria for the review.	Yes
Information sources	4	Specify the information sources (e.g. databases, registers) used to identify studies and the date when each was last searched.	Yes
Risk of bias	5	Specify the methods used to assess risk of bias in the included studies.	Yes
Synthesis of results	6	Specify the methods used to present and synthesise results.	Yes
RESULTS			
Included studies	7	Give the total number of included studies and participants and summarise relevant characteristics of studies.	Yes
Synthesis of results	8	Present results for main outcomes, preferably indicating the number of included studies and participants for each. If meta-analysis was done, report the summary estimate and confidence/credible interval. If comparing groups, indicate the direction of the effect (i.e. which group is favoured).	Yes
DISCUSSION			
Limitations of evidence	9	Provide a brief summary of the limitations of the evidence included in the review (e.g. study risk of bias, inconsistency and imprecision).	Yes
Interpretation	10	Provide a general interpretation of the results and important implications.	Yes
OTHER			
Funding	11	Specify the primary source of funding for the review.	No
Registration	12	Provide the register name and registration number.	No

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PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	p.1
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	p.1
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	p.2
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	p.2
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	Sect 2.3
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	Sect 2.2
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	Sect 2.2
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	Sect 2.1
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	Sect 2.1
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	Sect 2.1
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	Sect 3
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	Sect 2.1
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	Sect 2.1
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	Sect 2.1 & 2.3
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	Sect 2.1
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	Sect 2.1 & 3
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	Sect 2.1
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	Sect 2.1
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	Sect 2.1
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	Sect 2.1
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	Sect 2.1



PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	Sect 3.1
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	Sect 3.1
Study characteristics	17	Cite each included study and present its characteristics.	Supplemental Table S2
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	Sect 3.2
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	Supplemental Table S2 & Sect 3.2
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	Sect 3
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	Sect 3
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	Supplemental Table S2
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	Supplemental Table S2
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	Supplemental Table S2 & Sect 3
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	Sect 3.2
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	Sect 4
	23b	Discuss any limitations of the evidence included in the review.	Sect 4
	23c	Discuss any limitations of the review processes used.	Sect 4
	23d	Discuss implications of the results for practice, policy, and future research.	Sect 4
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	N/A
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	Sect 2
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	Sect 2.1
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	Acknowledgments
Competing interests	26	Declare any competing interests of review authors.	Competing Interests Statement
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	Supplemental Tables



PRISMA 2020 Checklist

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71.
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