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Systematic Review

Biomechanical Quantification of Children's Gross Motor Movement: A Systematic Scoping Review

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Abstract: Background/Objectives: Children continually learn and develop new motor skills towards mastery, resulting in varying movement patterns at different stages of motor competence. Understanding this progression and confidently recognising development delay requires synthesising the children's biomechanics literature. Firstly though, we must understand the past research and the approaches used. This review aims to identify and map the approaches and sources of the current literature in biomechanically quantifying the gross motor movement of typically developing children. **Methods**: A systematic scoping review was conducted in accordance with the Joanna Briggs Institute methodology. A database search of MEDLINE (Ovid), Scopus (Elsevier), ProQuest, CINAHL (EBSCO), and Web of Science identified English, peer-reviewed research biomechanically quantifying the movement of healthy children aged 3–12 years. Results include a bibliometric analysis and narrative summary. **Results**: Overall, 171 papers were included, representing a range of fields including footwear, injury, development, exercise, and activity. Country of origin and funding sources were equally variable. Walking was the predominantly assessed gross motor movement in children, followed by jumping and running. Equipment and facilities often resulted in more artificial settings, and important factors such as footwear used, testing environment, and condition familiarity were rarely reported. **Conclusions**: The literature results from diverse disciplines, institutions, and funding sources, but inconsistent reporting of conditions hinders synthesis. Future research is recommended to transparently report participant characteristics, environment, and testing conditions and to implement more ecologically valid protocols. Recommendations from this review will improve the quality of future research on children's movement.

Keywords: biomechanics; children; gross motor movement; methodology; bibliometrics

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1. Introduction

Gross motor skills are defined as whole-body movements that use large muscles for stabilization, separated into locomotor and object control [1]. As children age and practice different movements, they develop their gross motor skills towards mastering them [1]. This allows them to combine the fundamental movements into more complex actions that are used in adulthood. Motor development is described as the change in motor skills across the lifetime [2]. While there are milestones that most children are expected to have reached by certain ages, gross motor development is neither linear nor equal for every child, as children must continually adapt their motor skills to their episodically changing morphology [3,4]. However, improvements in motor development are based on the interaction between both an individual's biological and environmental factors [2]. Therefore, inter-child development of gross motor skills can vary.

Instrumented gait analysis is viewed as the gold standard for evaluating movement [5]. Adults' movement patterns are more extensively researched, but children have different development stages and perform movements differently than adults [6]. Therefore, the findings of these studies cannot be directly transferred to children, as they lack the external validity (ability to generalise and apply results to different populations, concepts, and contexts) and ecological validity (ability to generalise the results to real-world applications) [7,8]. Assessment of children's movement is useful for improving our understanding of motor development [9]. Through comparison of movement patterns between children, delayed development and clinical concerns and differences can be identified and the rehabilitation processes tracked [10]. However, to be able to confidently make clinical decisions, it is required to understand what the movement patterns of healthy, typically developing children are.

In recent decades, the literature quantifying and assessing the movements of children has been growing [11,12]. Research comes from a variety of fields, including paediatric medicine, health and safety, motor development, and performance. This has resulted in the absence of a standardised data collection methodology and reporting. Therefore, making synthesis of, and comparisons between, the literature is difficult. While previous reviews have been conducted on non-instrumented assessments of children's movement in healthy and clinical populations [5,13], at the time of the a priori protocol, there were no review papers published that synthesised the literature addressing biomechanical assessment of children's movement in regards to the bibliographic content, the populations assessed, and the methodological approaches taken. Furthermore, a preliminary search of MEDLINE and the Cochrane Database of Systematic Reviews and a JBI Evidence Synthesis conducted at the time of the a priori review protocol did not identify any current or underway systematic or scoping reviews. The research questions of this review, in full below, address the purposes of a scoping reviewed outlined by Munn et al. [14]: to examine how research is conducted on a certain topic or field, to identify and analyse knowledge gaps, and as a precursor to a systematic review. Therefore, a scoping review was selected as the most appropriate method of literature synthesis to review the broad research questions of this review and to identify gaps in the literature [14,15].

The proposed scoping review will identify and map previously used approaches. This will compare what has been done, specifically, the populations, settings, sources and descriptives, and methodological approaches previously assessed. It will highlight the gaps in the currently published research to provide recommendations for future research, leading to a better understanding of how children's biomechanics research has been conducted. Therefore, the aim of this scoping review is to identify and map the approaches and sources of the current literature in biomechanically quantifying the gross motor movement of typically developing children in all contexts, including different global populations, environmental settings, and methodological approaches. Results from this scoping review will help to establish the research question of a systematic review and inform the study design for primary data collection.

1.1. Review Questions

1. Where does the published research on typically developing children's biomechanics come from, for example, the country of origin and funding source, and how is it indexed?
2. What are the characteristics of the populations that have been assessed, and if relevant, how have the children been grouped?
3. What are the methods that have been used, including the setting and movements assessed, the measurements made, and any conditions or comparisons?

4. What are the gaps in the current literature that may, through this scoping review, be used to inform the direction of future research?

1.2. Inclusion Criteria

1.2.1. Population

For the purpose of this review, 'child' was defined as a minor aged 3–12 years old, which includes preschool age (3–5 years old) and middle childhood (6–12 years old). This scoping review considered studies that have typically developing human child participants only. Studies with a population focusing on or including children with any injuries or neuromuscular or developmental conditions that affect typical development of motor skills were excluded within the search terms and during the screening process. The exclusion of any studies featuring clinical populations was performed to prevent a skew in the types of movements assessed.

1.2.2. Concept

This review considered studies that explored or described the movement of children from a biomechanical perspective, including mention of spatiotemporal characteristics, kinematics, kinetics, plantar pressure, or electromyography.

1.2.3. Context

This review considered studies in any context to explore all settings and approaches that are being used for the quantification of typically developing children's movement.

1.2.4. Types of Sources

Peer-reviewed original research journal articles and short communications were considered eligible for inclusion, due to the expected small size of the field relative to research in adults. Qualitative studies were not considered, unless as part of a mixed-methods approach. Other reviews, as well as unpublished and grey literature, were not included in this review.

2. Methods

This scoping review was conducted in accordance with the JBI methodology for scoping reviews [16] and in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) [17]. This review was conducted in accordance with an a priori protocol (https://doi.org/10.17605/OSF.IO/A2MTR [PROTOCOL DOI]) [18].

2.1. Search Strategy

The search strategy aimed to locate published, peer-reviewed articles and short communications. This differs from the a priori protocol that stated to also locate unpublished articles. An initial limited search of MEDLINE (Ovid) and Scopus (Elsevier) was undertaken to identify eligible articles meeting the inclusion criteria. The text words contained in the titles and abstracts of relevant articles, and the index terms used to describe the articles, were used to develop a full search strategy. The search strategy, including all identified keywords and index terms, was adapted for each of the following information sources: MEDLINE (Ovid), Scopus (Elsevier), ProQuest, CINAHL (EBSCO), and Web of Science. The database searches were conducted on 1 November 2023. The full search strategies for each source are provided in File S1.

Only studies published in English were included due to the financial cost of full-text translation. Studies published from 1990 until the date of the database searches were included, with those published before being excluded in the screening process. The chosen date range represents the start of consistent publication of articles in the field and the beginning of government policies for children's physical education in the UK [19], marking an increase in interest of children's movement and health.

2.2. Source of Evidence Selection

Following the database searches, all identified records were collated in Endnote (V20.4.1, Clarivate Analytics; Philadelphia, PA, USA) and uploaded to review management software Covidence (Veritas Health Innovation; Melbourne, Australia). Covidence automatically removed identified duplicates, with others removed manually during screening.

Titles and abstracts were screened by one researcher for assessment against the agreed inclusion criteria for the review. The full texts of potentially relevant sources were imported into Covidence for in-detail assessment against the review criteria by two of three independent reviewers. Prior to full-text screening, a sample of 10 papers was randomly selected to confirm that the researchers were consistent in their interpretation of the exclusion criteria. Any conflicts that arose between two of the reviewers were resolved through discussion with the third reviewer. Full-text studies that did not meet the inclusion criteria were excluded, with the reasons presented in a PRISMA-ScR flow diagram (Figure 1). During full-text screening, studies that were identified to have walking as the only movement assessed, but that met all other inclusion criteria, were excluded but tagged for later comparison of movement type. Studies of exclusively sport-specific movement, such as baseball hit or swimming, were also excluded.

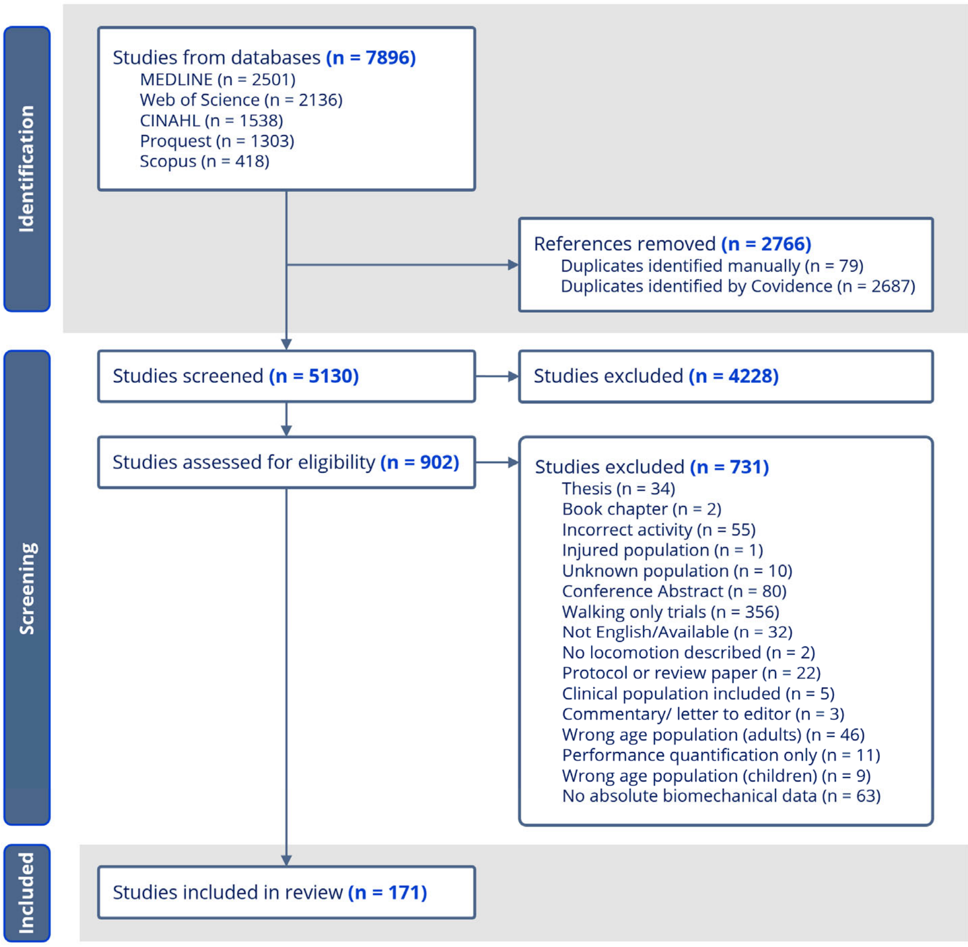


Figure 1. PRISMA flow diagram of search results, study selection, and inclusion process [20].

2.3. Data Extraction

From the papers that passed full-text screening, a sample of 10 was selected to represent a variety of study types and research areas. Each researcher performed data extraction of these papers using the data extraction tool. The resulting discussion led to alterations to the extraction tool originally developed in the a priori protocol [18] and an agreed consistent method of reporting data. Data extraction for each source was performed by one of the researchers in a macro-enabled Excel spreadsheet. A representation of the fields from the data extraction tool is presented in File S1, which includes specific details about the study, population, concept, and context.

2.4. Data Analysis and Presentation

A PRISMA-ScR flow diagram (Figure 1) is included to illustrate the progression of the screening process, with details of the number of studies that passed through each screening stage and the reasons for any exclusions. Extracted data are presented in tabular and graphical formats amidst a narrative description that describes how the results relate back to the research questions.

This scoping review includes basic bibliometric and scientometric analyses of the literature. This aims to provide an illustration of the patterns emerging within and between publications. VOSviewer (v1.6.20, Nees Jan van Eck and Ludo Waltman) is a freely available software used to create visual bibliometric maps. For this review, VOSviewer was used for co-occurrence and co-authorship analysis. The 2D distance-based maps created contain visual information about the nodes and the links between them. The distance corresponds to the strength of the link; greater co-occurrence between two nodes is represented by a thicker line; and the size of a node is proportional to its frequency. Nodes are classified by the software into clusters, shown as different colours. Numerical data for author and keyword occurrences are presented in the Supporting Information (File S2).

2.5. Ethical Considerations

This systematic scoping review extracted secondary data from existing publications available from the specified databases. Therefore, a submission to the institutional review board was not required.

3. Results

3.1. Study Inclusion

The search strategy of the databases (see File S1) identified 7896 sources, of which 2766 were duplicates, resulting in 5130 papers eligible for screening. The full breakdown of study selection and screening process is displayed in Figure 1. The main reasons for exclusion at full-text screening was due to incorrect activity (N = 55; walking only trials: N = 356), no absolute biomechanical data (N = 63), incorrect population (adults: N = 46; infants or adolescents: N = 9), or incorrect source type (conference abstract: N = 80; thesis: N = 34; protocol or review paper: N = 22). A further breakdown of reasons for exclusion is presented in Figure 1.

3.2. Characteristics of Included Studies

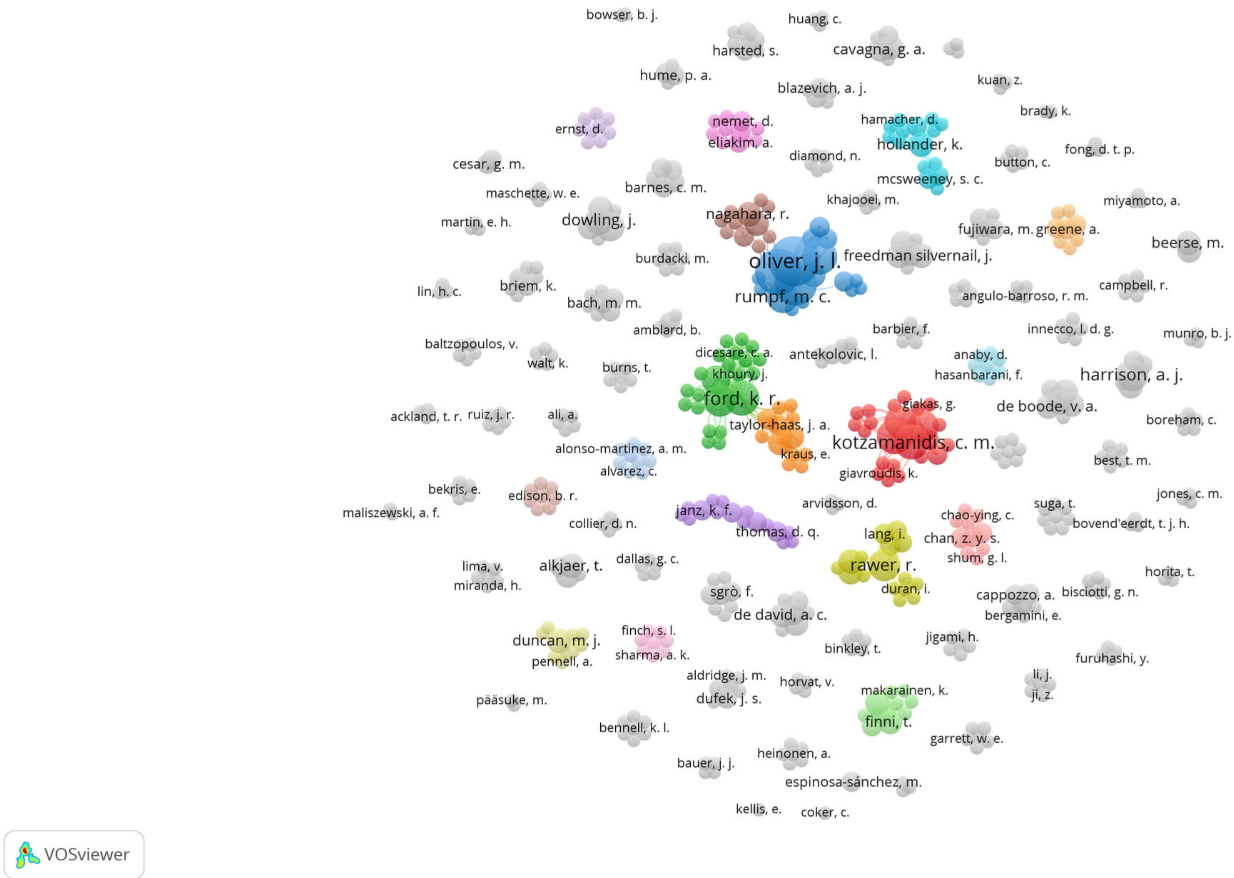
The characteristics of the included studies are attached as Supporting Information (File S3), with all references provided.

4. Discussion

4.1. Bibliometric Analysis

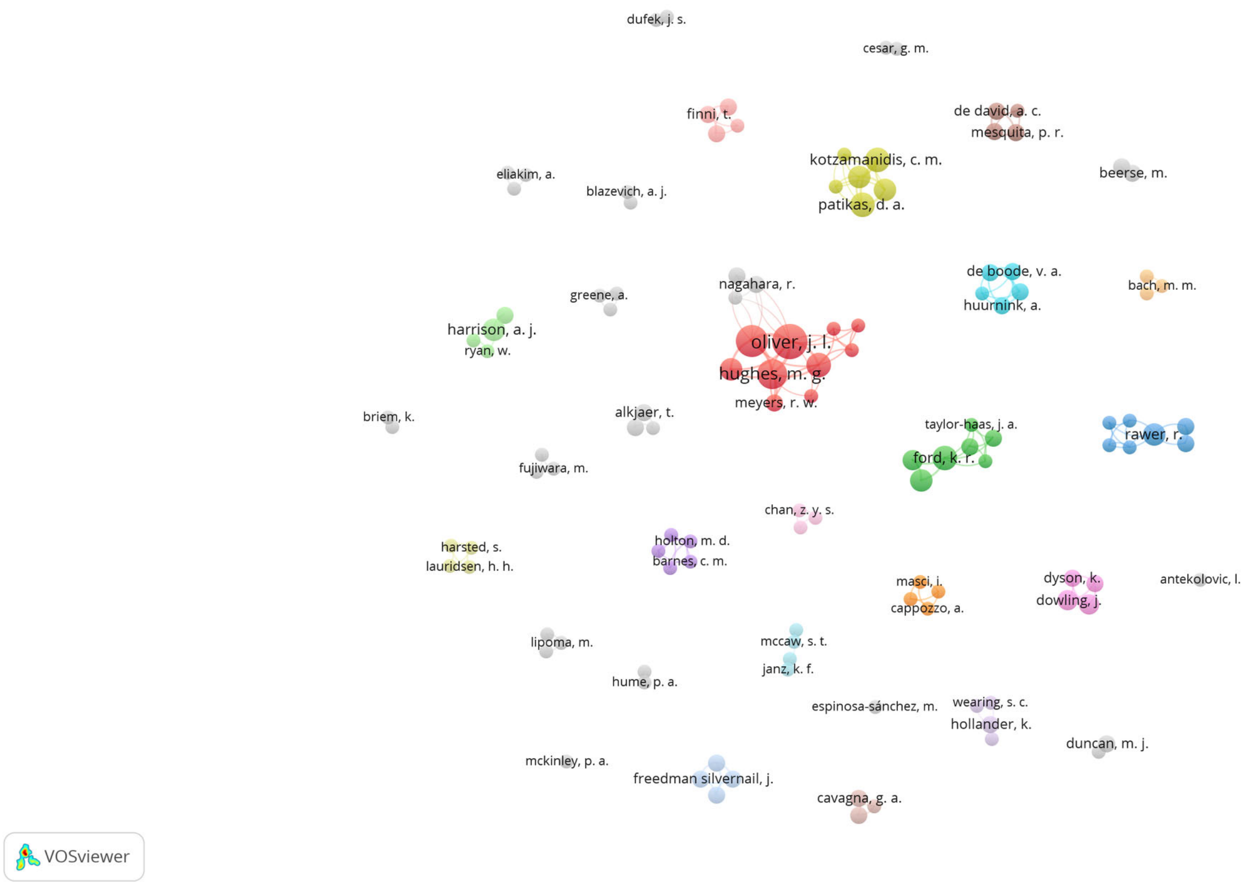
4.1.1. Authors

Network visualisation mapping of author co-occurrence (co-authorship) takes the list of each author and represents them as a node of size relative to the frequency of occurrences. Lines between each author (node) represent co-authorship on a journal article. Author co-occurrence for all appearances is presented in the network visualisation (Figure 2A,B). A lack of large clusters illustrates that the research is mostly undertaken within select groups and is not often multi-faculty or multi-disciplinary. From Figure 2A to Figure 2B, a change in filter to two or more occurrences of publication shows a reduction in clusters from 93 to 34, with 78.8% of authors publishing only once within the included criteria. This may highlight that a large proportion of the research is completed as a single study rather than continuous research within a group. Alternatively, it could also highlight how the field is growing and spreading to different areas of movement science, which inevitably will result in more research in these areas and more opportunities for multi-disciplinary approaches in the future.



(A)

Figure 2. *Cont.*



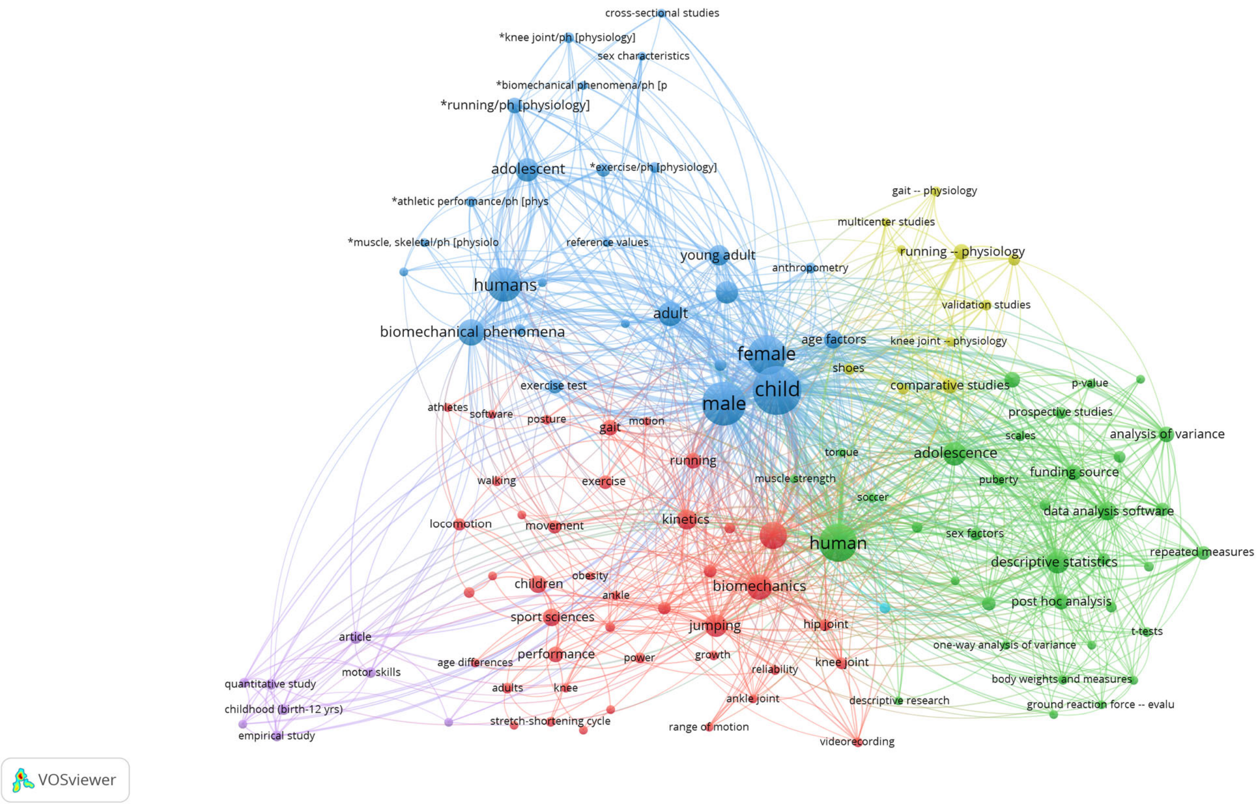
(**B**)

Figure 2. Network visualisation map of co-authorship for one or more occurrences (**A**) and two or more occurrences (**B**); from VOSviewer.

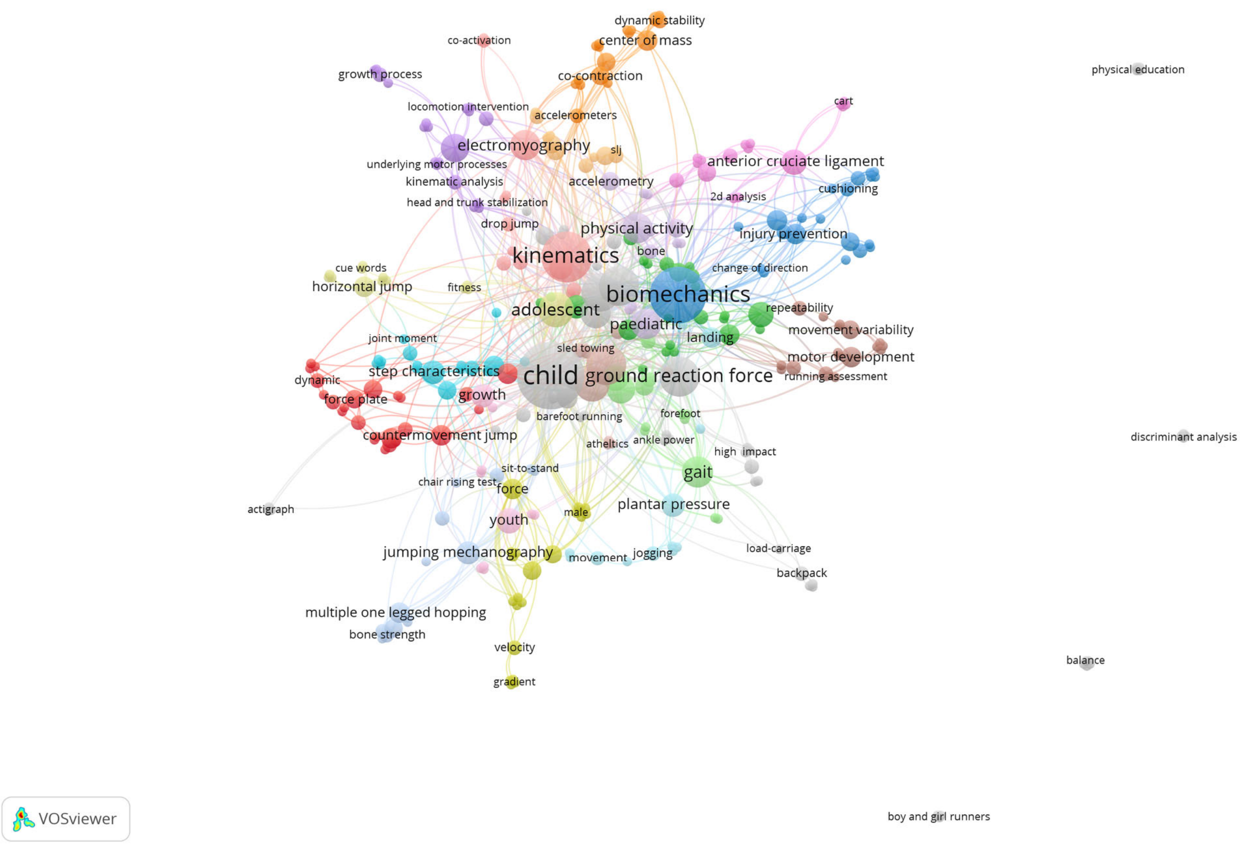
From the 171 papers, 566 authors were identified. The authors with the top 5 most publications were Oliver, J. (12 papers); Cronin, J. (10 papers); Hughes, M. (9 papers); Ford, K., Patikas, D., Kotzamanidis, C., and Lloyd, R. (6 papers); Bassa, E., Hewett, T., Lazaridis, S., Rawer, R., Rumpf, M., and Harrison, A. (5 papers). Total link strength is calculated by VOSviewer as the total number of co-authorships per author. The authors with the top 5 most collaborations with other authors were Oliver, J. (47 authors); Cronin, J. (37 authors); Ford, K. (35 authors), Hughes, M. and Patikas, D (33 authors); and Kotzamanidis, C. (30 authors). When relative to the number of publications, and filtering by three or more, Ford, K. has the greatest total link strength per publication (5.83, 6 papers) followed by Myer, G. (5.75, 4 papers), Bazett-Jones, D. and Garcia, M. (5.67, 3 papers), Patikas, D. (5.50, 6 papers), and Bassa, E. and Hewett, T. (5.40, 5 papers).

4.1.2. Keywords

When the keywords and key terms (including MeSH terms) are taken directly from the respective databases, there are 927 keywords without combining synonyms. Using a filter of four or more occurrences produces a network analysis of keyword co-occurrence (Figure 3A) wherein co-occurrences of keywords are connected by lines, and greater frequency is represented by the size of the individual nodes. The most-used key terms are 'child', 'male', 'female', 'human', and 'humans'. These are largely used to categorise papers for easier filtering at a broad level, rather than the specific content of the research.

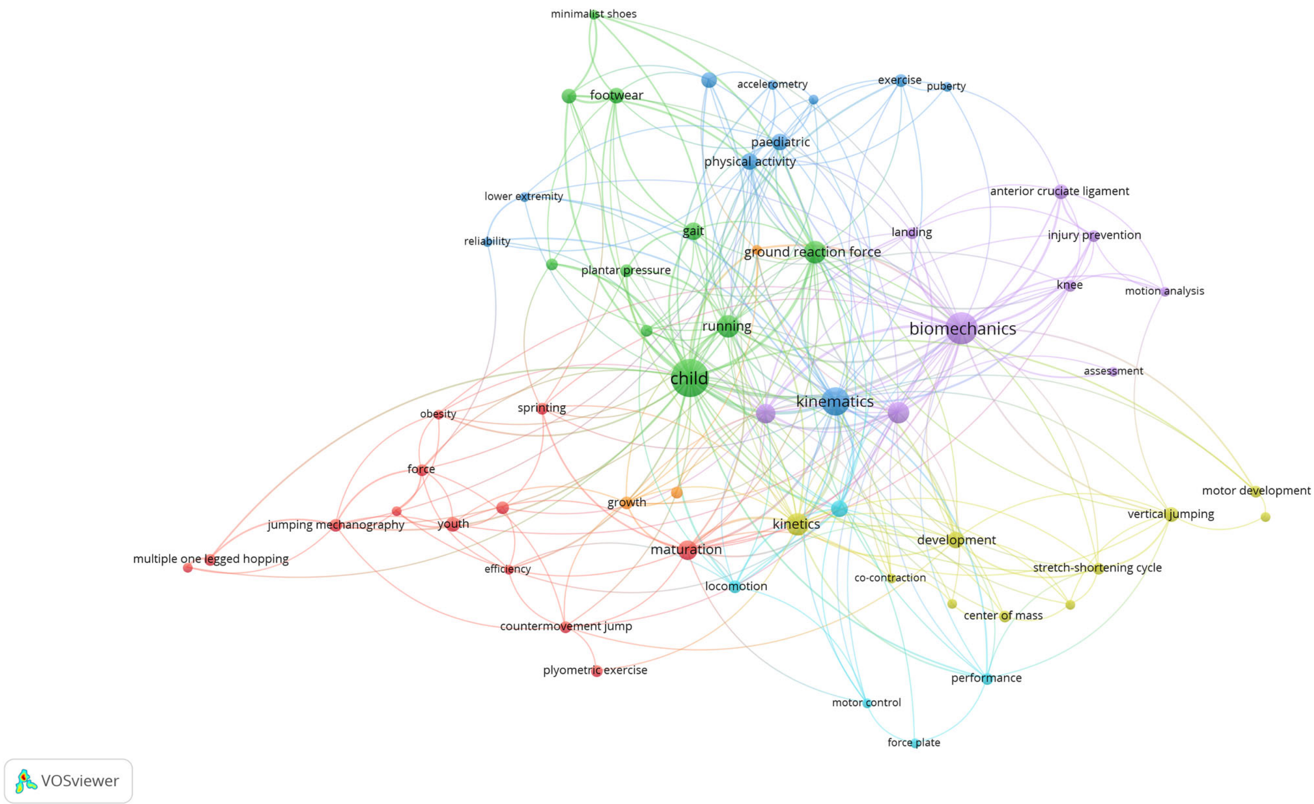


(A)



(B)

Figure 3. *Cont.*



(**C**)

Figure 3. (**A**) Keyword co-occurrences of keywords with four or more appearances sourced from keywords within the bibliography databases. Similar keywords were not combined. Asterisks (*) indicate MeSH terms. From VOSviewer. (**B**) Keyword co-occurrences of keywords with one or more appearances sourced from keywords within journal articles. A custom thesaurus was used for combination of similar words. From VOSviewer. (**C**) Keyword co-occurrences of keywords with three or more appearances sourced from keywords within journal articles. A custom thesaurus was used for combination of similar words. From VOSviewer.

An alternative is to use the keywords taken directly from the journal articles. While some journals may have restrictions on the keywords that can be selected, such as from a list or only words that do not appear in the title, using these keywords better represents the terms which are used by experts in the respective fields.

Using keywords with 1 or more occurrences (i.e., all 343 keywords) highlights the breadth of the research and the numerous fields within the children's movement literature (Figure 3B). With various niche areas of research present, it is important for a wide approach of research into the biomechanics of children's movement on multiple fronts. Several of the less frequently used keywords represent specific populations, approaches, or movements and link only with words used in that individual paper. Removing these by using keywords with three or more occurrences represents the most popular terms used by experts to index their research on children's movement. Compared with Figure 3B, Figure 3C displays the more consistently used keywords, and thus, the more researched areas. Clusters of keywords can be identified: research surrounding footwear, injury, development, force during movement, and exercise and activity.

4.1.3. Data Collection Location

Twenty-one percent of the publications are from the USA, with thirty-five papers. They are followed by the UK (15 papers), Australia (12), Japan (11), and Greece (10) in terms of publication frequency per country. These 5 countries' authors make up almost 50% of the research published in the field. The distribution of all the included sources per country is displayed in the world map (Figure 4). While authors from the USA published more papers than those of any other country, authors from Germany alone assessed more than 25% of the total child participants. They lead for children per publication at 462 children, with Iceland (202), Portugal (185), Japan (111), and Brazil (82) making up the rest of the top 5. Japan is the only country in the top five for publications and children per publication. The top three countries with the most publications are all English-speaking countries; therefore, it is possible that some research was not identified or was excluded during the search process due to publication in another language.

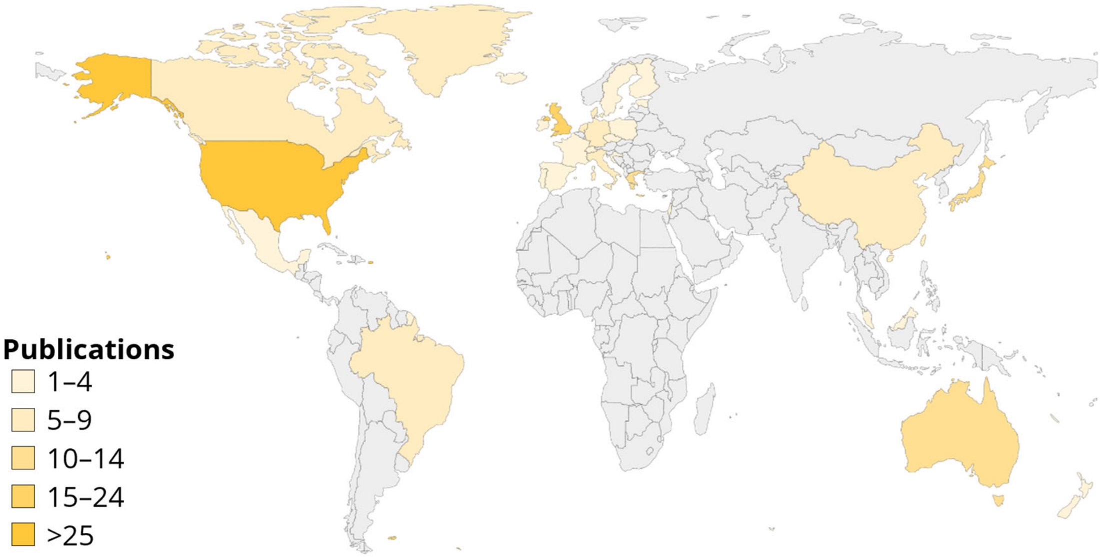


Figure 4. World map for distribution of publication output per country, using Visual Paradigm Online.

4.1.4. Year of Publication

The trend of publications per year surrounding biomechanical quantification of children's gross motor movement from 1990 onwards is shown in Figure 5. Following the start of interest in children's movement biomechanics the decade before, there are just a few papers during the 1990s, less than one a year on average, but increasing towards the latter half of the decade. From 2001, a burst of publications occurs across the 2000s, with an average of 2 publications per year. A second, steeper incline from the 2010s represents an increased interest in children's biomechanics, jumping to 9.1 papers per year. It appears that the trend and understanding of the importance of this research has continued to increase more recently, with 12.8 papers per year since 2020. Even with an apparent decline in publications since 2020, likely due to reduction in physical data collection during the COVID-19 pandemic, the last decade has produced 67.8% of the total identified research in this review. However, it should be considered that in general, more recently, there is also a greater increase in overall publication numbers, with more research conducted and more options of journals for publication.

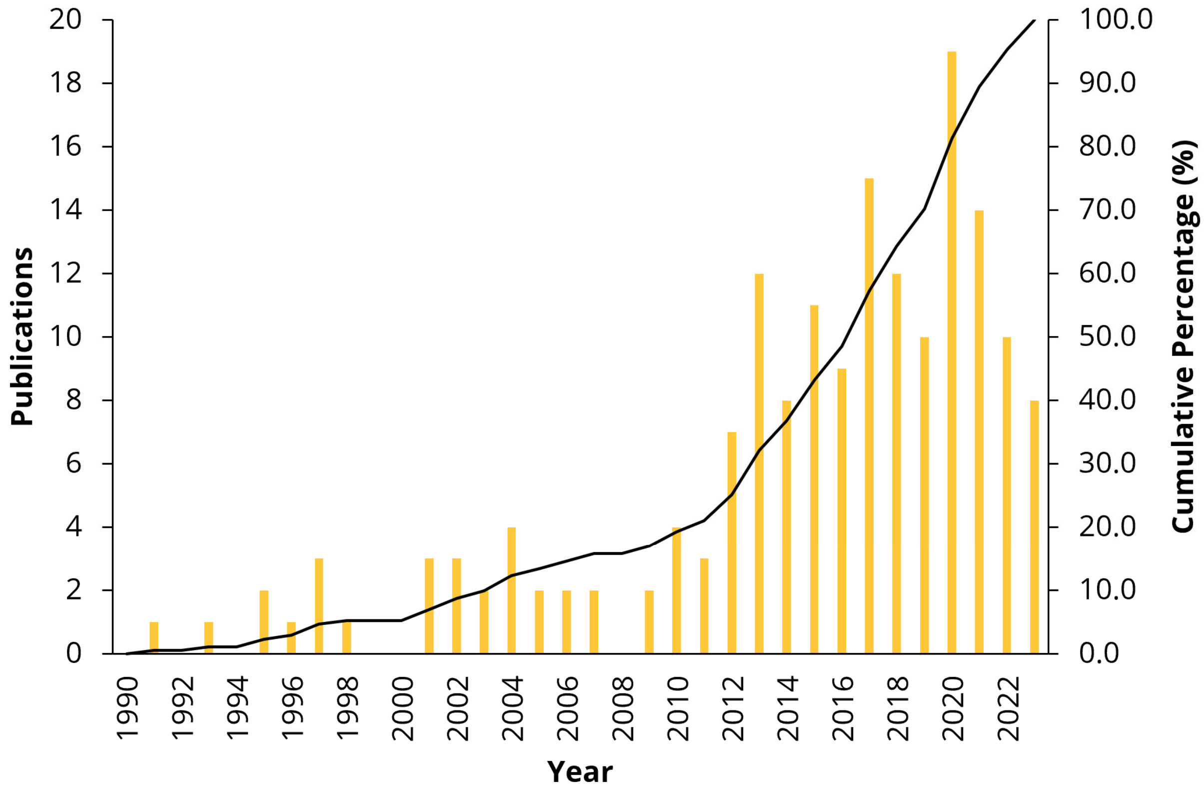


Figure 5. Publications per year (yellow bars) and cumulative percentage of all included studies (black line).

4.1.5. Funding

Approximately 40% of studies did not report any funding sources. However, stating the sources of funding is not required for all journals if not considered to be a potential conflict of interest. Of the remaining 102 studies that reported funding, the distribution of category of the funder/s is displayed in Table 1. While only one study disclosed that it was solely funded by an industry source, six additional studies were partially funded by, or had equipment and test conditions provided by, footwear companies.

Table 1. Distribution of funding bodies for studies that reported (% Reported: % of 102 papers), and of all (% All: % of 171 papers).

	Funding Body Category					
	Charity	**Council**	**Industry**	**University**	**Mixed/Multiple**	**None**
Sum	5	29	1	9	29	29
% Reported	4.9%	28.4%	1.0%	8.8%	28.4%	28.4%
% All	2.9%	17.0%	0.6%	5.3%	17.0%	17.0%

4.2. Population Characteristics

From 171 studies, over 11,400 participants were identified who were children that fit the age criteria of this review. However, this includes groups of children where the mean and one standard deviation or the range of ages overlaps the range of the inclusion criteria (3–12 years old). For example, within an intervention group from Sannicandro et al., a mean ± SD of 13 ± 1.1 years for boys would be included, but not the girls, at 14.1 ± 0.2 years, and all children would be included in the group with population characteristics 11.7 ± 3.6, 6–18 years old from Rozumalski et al. [21,22]. Of the 171 studies, 45 include adults (older than 18 years old) in the assessed population. Any adults included as comparison groups were not counted towards the final sum of participants. Of all 11,408 children, 47.4% and 44.9% were described as boys and girls, respectively. The remaining 7.7% of children did not have their sex detailed.

Aside from age, further population characteristics were seldom reported. Data were extracted from studies on health and training status. Definitions of health status were not clearly defined, with 'healthy' referring to either an absence of motor disorders or the child being categorised as healthy weight. From the 171 studies, health status was not reported in 81.9%. Eighteen studies had only healthy children, two with only overweight/obese children, eight with groups of healthy and overweight/obese, and three with mixed children. Training status of the children was more frequently reported, at 49.7% of studies reporting. For this review, 'untrained' was defined as participating in no activity, 'active' as participating in activities but not organised sports sessions, and 'trained' as participating in organised sports sessions with training. Of the studies, 15 had only untrained children, 26 had only active, 39 had only trained, and 2 had mixes of trained and untrained children together. Three studies had different groups within their data; two compared trained with untrained children, and one had an unknown and an untrained group.

Participants in the studies were grouped for comparison in a variety of ways, with some studies using two factor groupings. The distribution of group categories is displayed in Figure 6. Grouping reported as 'none' was selected for when no comparisons were made or comparisons were between the same participants. Comparisons between demographic characteristics (i.e., age, and sex) were the most common, with the top mode being between age groups. This theme continues with groups where the comparison populations were of adult participants. Groupings by sex (11.1% of studies), maturity status (9.4%), and by weight status and intervention (5.3% each) make the top 5.

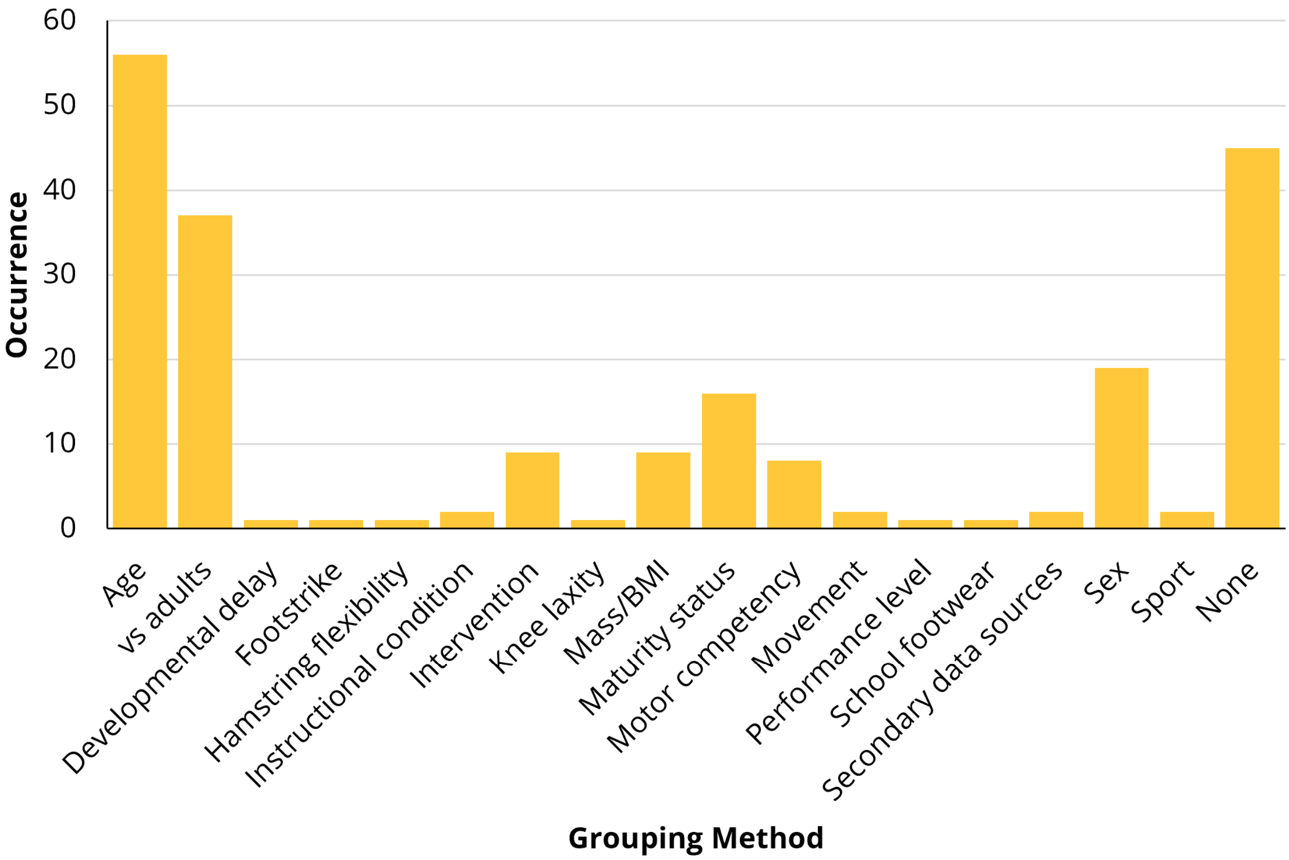


Figure 6. Bar chart for the categories of how participants were grouped within the identified studies.

When compared with adults, children have a large variation within their own movements during gait and jumping tasks, which diminishes with age [23–25]. Furthermore, the development of motor skills across childhood is influenced by multiple external factors [2]. This results in a wide array of motor competencies within any given age group. Through grouping participants by age, it does not consider the intra- and inter-subject variation in children's movement patterns, which may result in erroneous conclusions of age-group comparisons. Clinically important differences or minimal detectable changes are used to account for the variation in equipment and participants to determine what differences have a meaningful outcome [26]. Additionally, as with eight of the identified studies, participants may be grouped by categorisation of motor development. This would ensure that children who are at a similar developmental stage are grouped together regardless of their chronological age, thus minimising the between-subject variation in movement patterns [27].

4.3. Methodology

4.3.1. Study Design

During data extraction, studies were categorised by the study type from the following 11 categories, presented in Table 2: comparison, descriptive, intervention, longitudinal, methods, reference values, relationship, reliability, repeatability, validity, and variability. Studies could be placed into multiple categories, with one using different methods between the child and multiple adult groups [28]. The data type was largely discrete data (91.8% of studies), which refers to analysis of data of single points, for example maxima, minima, or ranges [29]. Continuous data refers to analysis of data across a timeseries of datapoints, for example, over a gait cycle or movement phase [29]. No studies analysed solely continuous data, while 7.6% of studies used mixed analysis. The remaining study had no analysis.

Table 2. Occurrence and distribution of study type.

Type of Study	Occurrences	Percentage (of 171 Studies)
Comparison	127	74.3%
Descriptive	5	2.9%
Intervention	17	9.9%
Longitudinal	10	5.8%
Methods	2	1.2%
Reference values	2	1.2%
Relationship	36	21.1%
Reliability	15	8.8%
Repeatability	6	3.5%
Validity	12	7.0%
Variability	5	2.9%

Over a third of studies did not report the data collection setting. Studies were labelled according to the original environment of data collection, for example, studies of secondary analysis (n = 2) were categorised as lab. Reports of gymnasium were categorised as indoor training facility unless specified as being a school gymnasium. Distributions of data collection setting are displayed in Table 3, with distribution of all studies and relative proportions of studies that report the setting. Many of the studies that did not report setting took place in an unspecified lab environment, of which the setting was not assumed. Of the papers that reported the data collection environment, 71.7% are set in a laboratory, which is an artificial environment made to reduce natural variability. Therefore, 28.3% of studies which report environment are in an environment that children are more familiar with, be that schools or sports training facilities.

Table 3. Distribution of the data collection setting for all studies, and for all that reported.

Data Collection Setting	Occurrences	Percentage (of 171 Studies)	Percentage (of Reported)
Lab	76	44.4%	67.3%
School	19	11.1%	16.8%
Indoor training facility	9	5.3%	8.0%
Hospital	5	2.9%	4.4%
Outdoor field test	4	2.3%	3.5%
Not reported	58	33.9%	-

4.3.2. Measurements

Fifty-five distinct movements were identified during the data extraction. This totalled to 363 movement conditions assessed across the 171 studies. A further 356 studies assessed walking only, which were excluded during full-text screening. The individual movements were collated into the following movement types and categories: walking, sprinting, running, and change in direction as locomotion movement separated into overground and treadmill; and vertical, horizontal, and landing as jumping movements (Figure 7). Multiple movements were assessed across many individual studies, including variations of the same movement, with speed, surface, or footwear conditions as possible options. It is important that movements assessed replicate what is typical for children and can discriminate between the individuals of the comparison groups. Without such ability, the assessment lacks known-group validity [8]. Furthermore, due to the unstructured nature of children's play, children often perform different movements than adults, and therefore, the external validity of movements selected should be tailored to child participants [30]. Not using movements relevant for a child population results in a lack of ecological validity [31].

The biomechanical characteristic of movement measured is dependent on the research questions of each study. The distribution of characteristics assessed are presented in Table 4. Kinematics and kinetics were measured in over half of the included studies. Plantar pressure was the least assessed biomechanical characteristic. Eighteen types of measurement device were recorded, with a force plate being the most often used, and eight devices were used fewer than five times (Table 5).

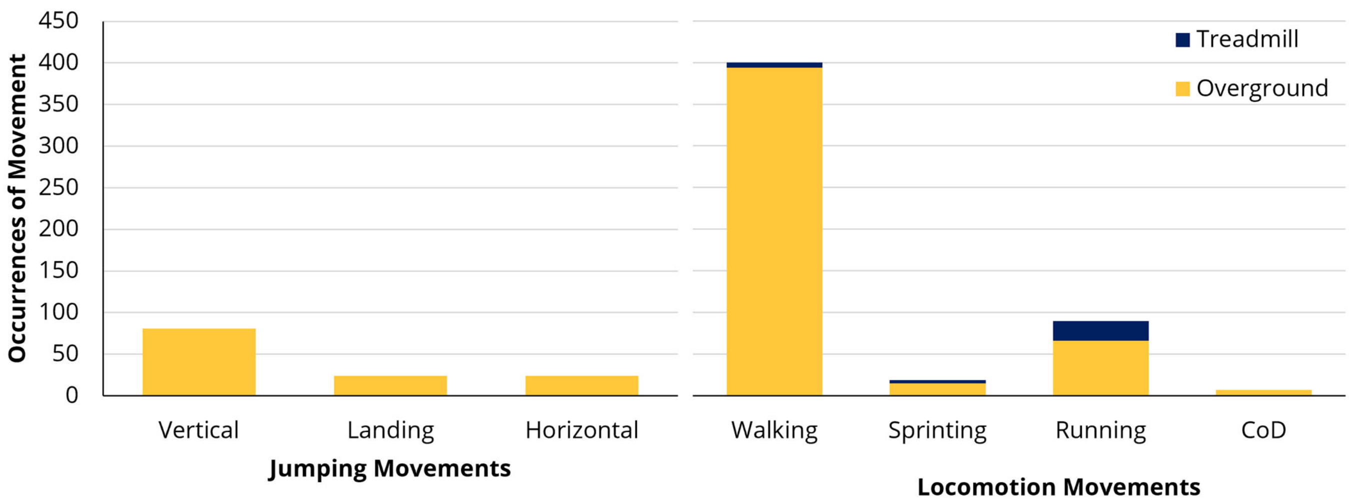


Figure 7. Occurrence of movements assessed, grouped by movement type and categorised as locomotion or jumping movements. Distribution of overground and treadmill assessment is displayed.

Table 4. Table of occurrence and distribution of biomechanical outcomes assessed in all included studies.

Biomechanical Outcome	Occurrences	Percentage (of 171 Studies)
EMG	19	11.1%
Kinematics	94	55.0%
Kinetics	112	65.5%
Plantar Pressure	10	5.8%
Spatiotemporal	73	42.7%

Table 5. Table of measurement device occurrences and distribution of use in all included studies.

Device Type	Measurement Device	Occurrences	Percentage (of 171 Studies)
Electromyography Electrode	EMG electrode	19	11.1%
	Textile EMG	3	1.8%
Motion Capture	Marker MoCap (vicon/qualisys)	57	33.3%
	Video camera	43	25.1%
	Markerless MoCap	4	2.3%
Force	Force plate	96	56.1%
	Dynamometer	5	2.9%
	Instrumented treadmill	12	7.0%
	Non-motorised force treadmill	4	2.3%
Spatiotemporal	Walkway (GAITrite)	1	0.6%
	Optojump	4	2.3%
	Foot switch	2	1.2%
	Contact mat	2	1.2%
Plantar Pressure	Pressure platform (Emed)	6	3.5%
	Insole pressure	1	0.6%
Inertial	Accelerometer	13	7.6%
	IMU	4	2.3%
Sonography	Ultrasound	1	0.6%

The aim of any research is to improve the understanding of an area, having first efficacy (internal validity), followed by effectiveness (external validity) as described by Steckler and McLeroy [7]. In a lay sense, firstly, does the protocol measure what we want in more controlled movements, and then, does it produce the same outcomes for children in a less controlled and more realistic environment. The identified studies were largely lab based, resulting in measurements for movements that were restricted by the lab space, often discontinuous linear movement over short duration. This creates a large question around the external validity of the measurements and whether the standardised lab movements replicate the broad spectrum of movement within the real play of a child [30].

A suggested methodological development of future footwear biomechanics research by Willwacher and Weir is to use larger scale, real-world, and representative data [32]. This may be achieved with alterations to the study design and data collection setting or to the movements assessed. Furthermore, with technological advances, the methods and analytical tools of human motion are constantly evolving more towards more real-world and representative data [33]. Through the requirements of collecting data in the real world, non-invasive and portable measurement devices have pushed for the development of equipment that can measure outside of ideal lab conditions. However, it is important that such devices are reliable and have been validated against laboratory-grade outcomes within child populations. Some of the more portable systems were utilised in the identified studies, but they appear sparsely compared with the lab-based equipment. While tracking the trend of portable equipment is outside the scope of this review, it is hypothesised that the use of real-world data equipment is expanding. As such, developments of this equipment and analytical methods have begun to provide data that are more practical, realistic, and meaningful compared with previous lab data [33].

4.3.3. Footwear

Over 50% of studies do not report the footwear that children used during testing. Use of own shoes and barefoot contribute around 15% each. In 11 studies, the footwear condition was described as, or could be assumed as, shod with no further details on the type of footwear. Any assumptions made for categorisation of shod or barefoot were based on photographs included by the authors showing the participants performing the tasks. Footwear was controlled within 15 studies, once through a standardised shoe for participants, and the rest providing footwear conditions of specific shoe types or a barefoot/shod comparison.

While footwear is widely known to affect the biomechanics of different movements in a range of populations [34–36], it is not as explored within child populations. However, as shoes affect children's walking gait, it could also be assumed that footwear would affect the biomechanics of other movements in some capacity [37]. A complete systematic review of the current literature on non-walking movements has not yet been conducted. The reporting of footwear type and the characteristics of footwear used in the literature is not sufficient. Largely, research specifically on the effect of footwear report taxonomy, but it is not common across all children's biomechanics studies. Along with no access to appropriate facilities for mechanical testing, the fact that only seven studies were partly or fully funded by footwear companies may explain why there is a lack information about the footwear used in the research. However, this does not explain the majority of studies that either do not report footwear conditions or only describe them as shod. For future synthesis of research, a consensus is required on the reporting of footwear characteristics within biomechanics studies [38].

4.3.4. Environment

A recent scoping review of IMU-based running gait analysis concluded that future biomechanics studies should transfer away from the laboratory environment to real-world assessments [39]. The results of the present scoping review also found that a majority of studies (71.7%) which report environment have measurements within laboratory or other settings unfamiliar to child participants, which may influence gross motor outcome measures.

In comparisons of infants' (18–37 months old) gross motor function in familiar and unfamiliar environments, no difference was observed [40]. Here, both measurement days had a different observer to ensure that there was no familiarity of the observer on the second day. The authors hypothesised that the presence of the caregiver may have increased the confidence of the children, as observed by others [41]. However, in clinical settings, older children (1–12 years old) with cerebral palsy have been observed to exhibit greater gross motor performance when in familiar environments, such as at home and at school versus in the community or clinic [42,43]. Further, assessment of hand movement in adults showed that differences in the movement pattern occur when the task is presented as a laboratory task versus an everyday-like task [44,45].

It is also plausible that children may perform tasks differently due to the presence of an observer, perceived expectations of the observer (the researcher), or an internal focus on movement, known as the Hawthorne effect [46,47]. In fact, increasing the number of observers has a linear relationship to the magnitude of changes in gait characteristics [48]. Observation can result in a stiffer-than-normal gait in children, characterised by reduced arm swing [46]. To minimise this effect, it has been recommended that a distractor should remove the attentional focus on gait without altering it through over-focus on the distractor itself [46]. This may also be achieved with an external goal to the required task, enabling focus on the outcome, not the task [49].

Therefore, quantification of children's gross motor movement in unfamiliar laboratory settings or with unfamiliar equipment could produce different results than in a familiar or real-world environment: an absence of ecological validity. Environments such as clinics or biomechanics laboratories are unfamiliar places with new faces and new equipment that can be overwhelming for children. In addition, the gold standards of biomechanics measurements often require a more invasive testing setup, for example, being surrounded by large equipment or cameras and requiring participants to wear less clothing for the attachment of markers and devices to the skin, all while asking them to perform a task 'normally'. Together, these factors may cause distraction during tasks, increase general discomfort and shyness, or increase the perception of observation.

5. Conclusions

The aim of this scoping review was to identify and map the approaches and sources of the current literature in biomechanically quantifying the gross motor movement of typically developing children from all contexts. While it is still a relatively new research area, since 1990, there has been increasingly greater growth and interest in children's movement biomechanics, with 171 papers published. This research covers a variety of populations (including studies with children and adults, boys and girls, healthy and overweight children, and trained and untrained children) from 31 different countries. More than half of the included studies measured kinematic and kinetic outcomes of movements, largely walking, followed by jumping and running, with comparisons between age groups (to other aged children and adults) the most predominant.

The collective aim of better understanding how children move has been addressed from a range of disciplines and fields (footwear, injury biomechanics, motor development, movement kinetics, and exercise and activity), that all connect through descriptions, methods, outcomes, and analyses of the research. However, as it is a new area of research, there are no standards as to what and how data are reported. This has left gaps in the knowledge of external factors within papers, such as key population characteristics (7.2% children with unknown sex; 81.9% and 50.3% of studies did not report health and training status, respectively), footwear used (unreported in 56.7% of studies), and data collection settings (unreported in 33.9% of studies). Research has predominantly taken place in laboratory facilities (67.3% of studies that reported the environment), often restricting the data to unrealistic short and linear movements, reducing the ecological validity of the findings.

Implications for Research

From reviewing the methodological approaches of the previous literature, the following recommendations for future research have been devised:

- Ensure transparent reporting of participant characteristics, including age, sex, and health and training status, if relevant. Consideration should also be given to the inter- and intra-variability of children's movement patterns within any assigned groups.
- Ensure transparent reporting of environment and testing conditions, including footwear used, surface, measurement setting, observers/researchers and surroundings, and the familiarity of these factors. The nature of the effect of footwear and

footwear characteristics on children needs to be established to further support the need for reporting.

- Address the ecological validity of assessment through the use of validated devices that allow for realism in the environment used alongside more realistic movements. For example, where possible, allow participants to partake in a space that is familiar to them, to wear their own clothes, and to use devices that do not provide tactile sensations. Assessed movements should better replicate a child's play, involving a variety of movements in multiple directions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/biomechanics5020028/s1, File S1: Database search strategies and data extraction tool; File S2: Data for co-authorship and keyword co-occurrence visualisation maps; File S3: Included study characteristics; File S4: Preferred Reporting Items for Systematic Reviews and Meta-Analyses 792 extension for Scoping Reviews (PRISMA-ScR) Checklist.

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Abbreviations

The following abbreviations are used in this manuscript:

PCC	Population, concept, context
PRISMA-ScR	Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews

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