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Network Analysis of Sport-Related Concussion Research During the Past Decade (2010–2019)

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Context: Research into sport-related concussion (SRC) has grown substantially over the past decade, yet no authors to date have synthesized developments over this critical time period.

Objective: To apply a network-analysis approach in evaluating trends in the SRC literature using a comprehensive search of original, peer-reviewed research articles involving human participants published between January 1, 2010, and December 15, 2019.

Design: Narrative review.

Main Outcome Measure(s): Bibliometric maps were derived from a comprehensive search of all published, peer-reviewed SRC articles in the Web of Science database. A clustering algorithm was used to evaluate associations among journals, organizations or institutions, authors, and key words. The online search yielded 6130 articles, 528 journals, 7598 authors, 1966 organizations, and 3293 key words.

Results: The analysis supported 5 thematic clusters of journals: (1) biomechanics/sports medicine (n = 15), (2) pediatrics/rehabilitation (n = 15), (3) neurotrauma/neurology/neurosurgery (n = 11), (4) general sports medicine (n = 11), and (5) neuropsychology (n = 7). The analysis identified 4 organizational clusters of hub institutions: (1) University of North Carolina (n = 19), (2) University of Toronto (n = 19), (3) University of Michigan (n = 11), and (4) University of Pittsburgh (n = 10). Network analysis revealed 8 clusters for SRC key words, each with a central topic area: (1) epidemiology (n = 14), (2) rehabilitation (n = 12), (3) biomechanics (n = 11), (4) imaging (n = 10), (5) assessment (n = 9), (6) mental health/chronic traumatic encephalopathy (n = 9), (7) neurocognition (n = 8), and (8) symptoms/impairments (n = 5).

Conclusions: The findings suggest that during the past decade, SRC research has (1) been published primarily in sports medicine, pediatric, and neuro-focused journals, (2) involved a select group of researchers from several key institutions, and (3) concentrated on new topical areas, including treatment or rehabilitation and mental health.

Key Words: mild traumatic brain injury, assessment, rehabilitation

Key Points

- Our findings represent the first network analysis of sport-related concussion (SRC) research and suggest that during the past decade, this literature has been published primarily in sports medicine, pediatric, and neuro-focused journals.
- Research on SRCs has emphasized epidemiology, assessment, and return to play, as well as emerging areas including rehabilitation and mental health.
- This network analysis of SRC research highlighted its benefits for identifying appropriate journals for article submissions, potential authors and institutions with whom to collaborate, and topics reflecting the direction in which the field is headed.

Sport-related concussion (SRC) continues to be a significant health concern affecting millions of athletes of all ages and levels, resulting in an estimated US economic burden up to $17 billion annually. This heterogeneous injury involves myriad signs, symptoms, and impairments, and although many athletes recover within a few weeks,[1] some take months or longer.[2] Given the large number of affected athletes and burden of this injury, the field of SRC research has experienced tremendous growth during the past decade. In fact, a search of the term *sport-related concussion* in PubMed on January 24, 2020, yielded 1822 peer-reviewed articles published during the previous 10 years. This work has enhanced our empirical and clinical knowledge of SRC in areas such as epidemiology, identification, assessment, recovery, and rehabilitation.[3] However, investigators have yet to empirically synthesize developments and trends in SRC research during this period of rapid growth.

Research and clinical practice in concussion have evolved substantially since the late 1990s and early 2000s, when the literature emphasized SRC identification by focusing on grading scales, symptoms, and the role of loss of consciousness.[4] As the field evolved from 2005 to 2010, the focus shifted to biomechanics, assessments of balance and cognitive performance, age and sex differences, recovery time, rest-based intervention, and consensus statements designed to inform clinical care.[5] More recently, SRC research has progressed to include ocular and vestibular assessments, advanced neuroimaging, fluid biomarkers, clinical subtypes or profiles, and rehabilitation.[3,6,7] During the past decade, the paradigm of prescribed rest as the primary or sole management strategy for SRC

was challenged by empirical evidence that supported more-active approaches.[8] The field has also begun to shift toward earlier, more-active interventions that target specific symptoms and impairments.[3] Empirical evidence has provided the basis for these theoretical and clinical paradigm shifts and will continue to do so as the work moves forward. However, the field of SRC research has lacked introspective analyses of past research trends to help guide future paradigms and approaches to clinical care. An empirical analysis of trends in SRC research during the past decade could inform future lines of inquiry and areas for clinical advancement.

Network analysis provides a useful tool for objectively assessing the bibliographic trends of a scientific field.[9] On the basis of the outcome of interest (eg, journals, institutions, and authors) network analysis produces an interconnected bibliometric map from associations among outcomes.[9,10] Given the rapid growth in SRC research over the previous 10 years, this method could offer a greater understanding of recent trends that may otherwise go unnoticed, including journals, key research institutions, and authors. This information could inform a foundational basis for future studies and collaborations.

The purpose of our study was to evaluate trends in the SRC literature using network analysis based on a comprehensive search of original, peer-reviewed research articles involving human participants published between January 1, 2010, and December 15, 2019. Specifically, we used network analysis to evaluate associations in the following areas: (1) peer-reviewed journals, (2) organizations and institutions, (3) authors, and (4) relevant key words.

METHODS

We identified articles in the Web of Science Core Collection using key terms to encompass all forms of SRC (eg, *concussion*, *sport-related concussion*, *cerebral concussion*) or mild traumatic brain injury (mTBI; eg, *mild traumatic brain injury*, *mild brain injury*, *mild TBI*) research from 2010 to 2019 that involved human participants. The search was conducted on December 15, 2019. The search was delimited to the previous decade to focus on recent trends in SRC research. The search was further refined to only original articles, reducing the total number to 6130 from 10 086. All bibliometric data, including title, authors, organizations, abstract, key words, and bibliography, were imported into network-analysis software (version 1.6.13; VOSviewer, Leiden University, Leiden, The Netherlands).[9] A detailed mathematical description of the software and how it applies a variant of a multidimensional scaling algorithm can be found in a report by van Eck et al.[9] Search terms and their variants were removed from the analysis. Clusters (ie, groups of interconnected nodes) were derived for each map using a resolution of 1.0, attraction of 2, repulsion of 1, minimum cluster size of 5, and resolution of 2.[11] Clusters were subjectively named on the basis of the overarching themes of the individual cluster groups. With regard to interpreting the maps, connecting lines indicate an association between nodes. More lines indicate more dense connections between the given node and its connecting nodes.[9] Similarly, closer proximity between 2 nodes reflects a stronger association than 2 nodes at a farther distance.[9] Central location of a node indicates more connections, whereas more distal locations indicate fewer connections.

The online search yielded 6130 articles, 528 journals, 1966 organizations, 7598 authors, and 3293 key words. *Citation analyses*, or assessments of the number of times journals, organizations, or authors cite one another, were conducted to analyze journals, organizations, and authors using specific minimum inclusion criteria: 5 publications for journals, 5 publications for organizations, and 10 publications for authors. Outcomes for each analysis were the number of articles, citations, total link strength, and clusters. For organization- and author-cluster reporting, the *hub*, or the most highly interconnected organization or individual author, is reported as the cluster name. To analyze the top key words in concussion research, a *co-occurrence analysis* (ie, assessment of the number of articles in which multiple key words occur together) was performed with a co-occurrence minimum of 10 for inclusion. Variants of the search terms and populations were removed from the analysis in order to investigate the key topics that have been evaluated. Outcomes for key-word analysis are occurrences, total link strength, and clusters; the top 10 (ordered by most SRC publications within the study period) were also analyzed for journals, organizations, authors, and key words using full counting.

RESULTS

The number of publications, citations, and total link strength for the top 10 journals, organizations, and authors as well as the number of occurrences, citations, and total link strength for the top key words from 2010 to 2019 are presented in Table 1. The top 10 journals, organizations, and authors accounted for 48.1%, 34.1%, and 20.3% of the total SRC publications, respectively (journals = 59, organizations = 50, authors = 148). The top 10 key words from 2010 to 2019 accounted for 32.3% of the total occurrences (n = 78). The top 5 journals per cluster are shown in Table 2.

Network analysis revealed 5 journal clusters (categories) for SRC research (Figure): (1) biomechanics/sports medicine (n = 15), (2) pediatrics/rehabilitation (n = 15), (3) "neuro focused" (eg, neurology, neurotrauma, neurosurgery; n = 11), (4) general sports medicine (n = 11), and (5) neuropsychology (n = 7). Among institutions that published SRC research, 4 clusters were identified (Figure B): (1) University of North Carolina (n = 19), (2) University of Toronto (n = 19), (3) University of Michigan (n = 11), and (4) University of Pittsburgh (n = 10). Among authors who published SRC research, 7 clusters were identified (Figure C): (1) Kontos (n = 32), (2) Iverson (n = 27), (3) McCrea (n = 27), (4) Broglio (n = 25), (5) Kerr (n = 16), (6) Kroshus (n = 14), and (7) Guskiewicz (n = 7). Network analysis revealed 8 key-word clusters for SRC research published from 2010 to 2019 (Figure D): (1) epidemiology (n = 14), (2) rehabilitation (n = 12), (3) biomechanics (n = 11), (4) imaging (n = 10), (5) assessment (n = 9), (6) mental health/chronic traumatic encephalopathy (n = 9), (7) neurocognition (n = 8), and (8) symptoms/impairments (n = 5).

Table 1. Overall Top 10 Journals, Organizations, Authors, and Key Words in Sport-Related Concussion Publications, 2010–2019

Variable	Articles	Citations	Link Strength
Journal			
American Journal of Sports Medicine	115	4763	2516
Archives of Clinical Neuropsychology	43	692	594
Brain Injury	121	1397	1125
British Journal of Sports Medicine	87	3426	1472
Clinical Journal of Sport Medicine	112	2250	1428
Frontiers in Neurology	44	204	474
Journal of Athletic Training	132	2530	1701
Journal of Head Trauma Rehabilitation	46	743	582
Journal of Neurotrauma	145	2906	1445
Journal of Science and Medicine in Sport	60	591	455
Organization			
Boston Children's Hospital	74	1269	2935
Harvard Medical School	83	441	1961
Harvard University	81	2699	3068
Medical College of Wisconsin	72	1426	2478
University of Calgary	95	1587	2446
University of Michigan	101	2190	2646
University of North Carolina	155	3503	4181
University of Pittsburgh	108	2975	3254
University of Toronto	135	1790	2049
University of Washington	88	1268	2232
Author			
Collins	46	2030	2460
Comstock	51	1761	1795
Covassin	56	1629	2291
Guskiewicz	76	2997	3460
Kerr	68	1245	2336
Kontos	57	1805	2569
Marshall	52	1437	1992
McCrea	55	1398	2562
Meehan/Broglio (tie)	61/61	1779/1786	2420/2804
Mihalik	53	1020	1859
Key Words	**Occurrences**	**Citations (Average)**	**Link Strength**
Balance	51	12.8	60
Biomechanics	55	17.9	25
Chronic traumatic encephalopathy	53	17.7	19
Epidemiology	82	18.9	25
Impact	73	19.3	53
Postconcussion syndrome	49	26.8	37
Recovery	41	16.7	39
Rehabilitation	46	13.6	42
Return to play	70	20.5	46
Symptoms	50	33.4	52

DISCUSSION

We are the first to use network analysis to evaluate trends in SRC literature among peer-reviewed journals, institutions, authors, and key words. The results demonstrate that SRC research has been published primarily in sports medicine and secondarily in pediatric and neuro-focused (ie, combined neurology, neurosurgery, neurotrauma) journals. Four key, highly interconnected institutions—the University of North Carolina, University of Toronto, University of Michigan, and University of Pittsburgh—disseminated a disproportionate amount of SRC research (Figure B). Seven author clusters were also identified, with many of the author hubs located at the key institutions (Figure C). Eight key-word clusters were identified (Figure D), suggesting that epidemiology, assessment evaluation, and return to play remain central themes, with rehabilitation and mental health concerns emerging as newer focus areas.

Journals

Given that the overarching topic of the current analysis was concussion in sport, it was not surprising that sports medicine journals such as the *Journal of Athletic Training*, *American Journal of Sports Medicine*, *Clinical Journal of*

Table 2. Top 5 Journals Within Each Cluster of Sport-Related Concussion Publications, 2010–2019

Cluster	Journals	Publications	Citations	Total Link Strength
Biomechanics/sports medicine	*British Journal of Sports Medicine*	87	3426	1472
	Journal of Science and Medicine in Sport	60	591	455
	Medicine & Science in Sports & Exercise	43	1163	761
	Annals of Biomedical Engineering	29	756	347
	Journal of Sport Rehabilitation	23	82	121
Pediatrics/rehabilitation	*Clinical Journal of Sport Medicine*	112	2250	1428
	Journal of Head Trauma Rehabilitation	46	743	582
	Orthopedic Journal of Sports Medicine	42	276	329
	Pediatrics	42	2091	1017
	Physician and Sportsmedicine	39	256	356
Neuro focused	*Journal of Neurotrauma*	145	2906	1445
	Frontiers in Neurology	44	204	474
	Journal of Neurosurgery: Pediatrics	33	602	542
	PLoS One	31	552	276
	Neurosurgical Focus	24	505	339
General sports medicine	*Journal of Athletic Training*	132	2530	1701
	American Journal of Sports Medicine	115	4763	2516
	Sports Health	36	246	359
	International Journal of Athletic Therapy and Training	23	22	143
	Journal of Neurological Sciences	14	501	221
Neuropsychology	*Brain Injury*	121	1397	1125
	Archives of Clinical Neuropsychology	43	692	594
	Journal of the International Neuropsychology Society	28	605	417
	Applied Neuropsychology: Child	26	149	311
	Journal of Clinical and Experimental Neuropsychology	25	291	199

Sport Medicine, and *British Journal of Sports Medicine* were primary outlets for SRC research (Tables 1 and 2). The largest journal cluster (n = 15) was biomechanics/sports medicine. As motion-analysis and engineering technology has progressed over the past decade, this technology has been applied to SRC research to investigate topics such as the role of subconcussive impacts,[12] a force threshold for sustaining an SRC,[13] sex differences in neck and head control,[14,15] and optimizing helmets for SRC prevention and identification.[16] Pediatrics/rehabilitation was tied for the largest cluster (n = 15), with the most peer-reviewed publications during the study period (478, 19% more than the next-highest cluster). This body of research consisted of risk-factor identification for prolonged recovery or persistent post-SRC symptoms, such as initial symptom burden, preinjury mood disorders, personal or family history of migraine, or vision or vestibular dysfunction preinjury or postinjury.[3,17,18] This work provided important contributions to our clinical understanding of SRC because clinician knowledge about preexisting risk factors can help guide management and intervention strategies. Additional management strategies and safe return-to-play or return-to-school guidelines were also a primary focus of this research cluster, reflecting the emphasis on pediatrics.[19–21]

The third largest cluster was neuro focused, which addressed an enhanced clinical understanding of SRC heterogeneity, treatment efficacy, and assessment of objective biomarkers (eg, cerebral blood flow, magnetic resonance imaging, diffusion tensor imaging, and blood biomarkers; Tables 1 and 2).[22,23] Specifically, the classification of different SRC presentations into "profiles" or "subtypes" and the development of tools to identify these different SRC types were in this cluster.[8] The purpose of identifying SRC profiles is to provide a framework for interventions that target individual responses to SRC.[24] General sports medicine was the fourth largest cluster and focused on validation and implementation of assessments such as balance and postural stability, gait, vestibular and ocular impairment, and neurocognitive tests for identification and prognostic utility. Sideline assessments, such as the Sideline Concussion Assessment Tool and symptom-reporting scales, were also emphasized in this cluster. The final journal cluster was neuropsychology (n = 7). A focus of this cluster was neurocognitive and neuropsychological testing because these measures are commonly used to inform the clinical diagnosis.[25,26] This cluster also highlighted symptom-reporting measures and their diagnostic and prognostic value to the clinician. Although the topical areas in this cluster were broad, the core was research centered on improving the neuropsychologist's assessment and management of patients with SRC.

Institutions and Authors

A select group of key institutions and authors acted as the primary SRC research hubs over the past decade (Table 1 and Figure B–D). The University of North Carolina has published SRC research in topical areas such as knowledge of and attitudes toward SRC among players and health care professionals, biomechanics of head impacts, and balance assessments over the past decade.[13,27–29] Epidemiology has also been a focus of this group.[30,31] The University of Toronto has addressed the potential role of imaging and other diagnostic tools for identifying concussion and persistent symptoms, as well as pediatric concussion.[32,33] The University of Pittsburgh was another hub (n = 10) identified in this analysis. Its authors emphasized a clinical profile approach to SRC management, risk factors, and vestibular and ocular assessment and impairment after the injury.[6,7,34] This group has also focused on sex differences in presentation and recovery, clinical assessments, and

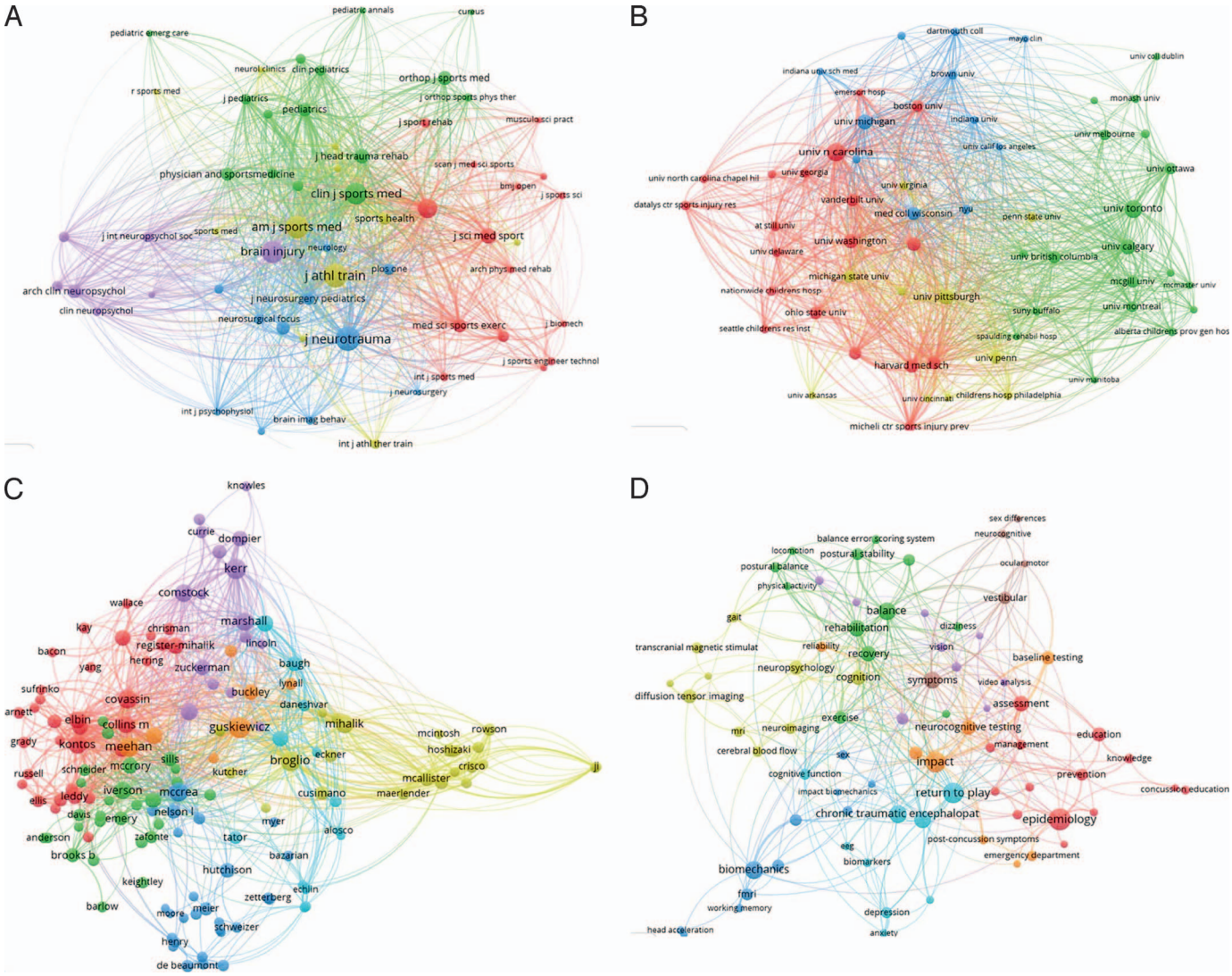

Figure. A, Network map of journals that published sport-related concussion research from 2010–2019. Five clusters were identified: (1) biomechanics/sports medicine (red), (2) pediatrics/rehabilitation (green), (3) neurotrauma/neurology/neurosurgery (blue), (4) general sports medicine (yellow), and (5) neuropsychology (purple). B, Network map of organizations that published sport-related concussion research from 2010–2019. Four clusters were identified (named for the primary hub): (1) University of North Carolina (red), (2) University of Toronto (green), (3) University of Michigan (blue), and (4) University of Pittsburgh (yellow). C, Network map of authors who published sport-related concussion research from 2010–2019. Seven clusters were identified (named for the primary hub): (1) Kontos (red), (2) Iverson (green), (3) McCrea (blue), (4) Broglio (yellow), (5) Kroshus (light blue), (6) Kerr (purple), and (7) Guskiewicz (orange). D, Network map of key words used in sport-related concussion publications in peer-reviewed journals from 2010–2019. Eight clusters were identified 1. epidemiology (red), 2. rehabilitation (green), 3. biomechanics (navy blue), 4. imaging (yellow), 5. assessment (purple), 6. mental health/chronic traumatic encephalopathy (light blue), 7. neurocognition (orange), 8. symptoms/impairments (brown).

predictors of prolonged recovery from SRC.[35,36] The University of Michigan, the final hub (n = 11) identified in this analysis, published research on the utility and efficacy of clinical assessments[37] and the role of biomechanics/head impacts.[38] Together, these institutions represent the most prolific hubs of SRC research over the previous decade.

Key Words

As the largest cluster and top co-occurring key word, *epidemiology* was a primary area of SRC research over the decade, with close associations to knowledge, education, and prevention (Tables 1 and 2; Figure D). Rehabilitation was the second-largest cluster, with 3 of the top 10 most co-occurring key words (eg, *balance, rehabilitation, recovery*; Table 1). The rehabilitation cluster was associated with key words from research on balance assessments, gait, and physical activity, among other topics. Similarly, the biomechanics cluster included research on head impacts and acceleration. Imaging and assessment were the only 2 clusters not represented by a key word in the top 10 most co-occurring key words of the decade, which may be related to the broad nature of their associations (Figure D). The imaging cluster encompassed research using imaging modalities, such as magnetic resonance imaging, as well as investigations of neuropsychology and cognition. The inclusion of neuropsychology and cognition in this cluster

was likely related to neurocognitive metrics being the clinical assessment of choice during imaging. The assessment cluster was linked with research that used key words such as *video* and *vision analysis*, among others.

During the last decade, research on SRC has also emphasized the long-term effects of the injury, as evidenced by the mental health/chronic traumatic encephalopathy cluster's inclusion of 3 of the top 10 key words: *return to play*, *postconcussion syndrome,* and *chronic traumatic encephalopathy* (Table 1). This cluster also included *anxiety* and *depression*, 2 mental health topics that are increasingly viewed as important areas of focus in SRC research. The co-occurrence of these key words is possibly related to increased public concern over the association of SRC with the development of neurodegenerative diseases or mood disorders later in life. The neurocognition cluster included *impact* as a top 10 key word, which may reflect the commonly used computerized neurocognitive test (ie, Immediate Post-concussion Assessment and Cognitive Testing [ImPACT Applications, Inc]) or head impacts or impact exposure. Finally, the symptoms/impairments cluster contained typical impairments associated with the injury, such as vestibular, oculomotor, and neurocognitive impairments, as well as general symptoms.

Strengths and Limitations

Our findings contribute to the broader concussion literature by describing the relationships among topical areas (ie, journal clusters) and individual journals that often publish research on those topics. This study provides a useful resource for clinicians and researchers alike to identify the top peer-reviewed information sources on their topic of interest (Table 2). The key-word analysis (Table 1 and Figure D) supplies our major contribution to the literature in revealing the co-occurrences, which can elucidate trends during this period of enormous growth in SRC publications. For example, *rehabilitation* being the 9th-ranked key word of the decade is a critical finding in our opinion (Table 1). This result is important, given that approximately 15 to 20 years ago, SRC was still predominantly viewed as a homogeneous injury that required a "one- size-fits-all" treatment approach.[39] Thus, rehabilitation would likely not have been a central focus of research during that time because everyone with concussion was usually treated with the same approach. Researchers can build on the key findings of the past decade to initiate more-informed therapeutic trials to enhance our understanding of the efficacy of certain rehabilitation strategies. To maximize the potential of the next decade, SRC investigators can use the foundational research we presented to identify the most pertinent areas for future inquiry.

Another critical aspect of informing treatment practice is the mitigation of potential long-term effects of SRC, such as postconcussion syndrome and chronic traumatic encephalopathy. Our key-word analysis of the past decade indicated substantial interest in these long-term effects (Table 1). *Recovery* was also a top key word. The significant co-occurrence of these key words was possibly related to the increased public concern over an SRC history and the development of neurodegenerative diseases later in life.[40] Potential long-term effects of concussion are another area of SRC research that can benefit from intervention studies to obtain high-quality evidence. Our results can be used by clinicians and investigators to encourage collaboration and inform future lines of research in this area, among others.

The limitations to this type of analysis are worth noting. The study was delimited to SRC research published during 2010–2019, so the findings presented here do not reflect concussion research before the inclusion date or in other populations (eg, military, accidents, assaults). In addition, each cluster and key word could not be covered exhaustively due to space constraints. Therefore, the summary of journal clusters and key words is informed by our subjective decision making based on the results of the analysis. The software used in the network analysis is limited to word detection and cannot detect capitalizations of words. As such, the key word *impact* could be referring to a physical contact that may have resulted in a concussion or a popular computerized neurocognitive test (ie, ImPACT). Given the close proximity of *impact* and *neurocognitive testing* in the network map (Figure 1D), we suspect it was the latter, but this assumption cannot be determined definitively. Another limitation involved the space constraints in the network maps that resulted in certain nodes not having labels.

CONCLUSIONS

Our understanding of SRC identification, assessment, and rehabilitation has grown considerably over the past decade. The current findings represent the first network analysis of SRC research and suggest that, during the past decade, SRC research has (1) been published primarily in sports medicine, pediatric, and neuro-focused journals, (2) involved several key institutions within a broad field, and (3) centered on epidemiology, assessment, and return to play, as well as emerging areas including rehabilitation and mental health. This study also highlights the benefits of using a network analysis of SRC research to identify appropriate journals for article submissions, potential authors and institutions with whom to collaborate, and topics reflecting the directions in which the field is headed.

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