Gait & Posture 71 (2019) 227–233

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

The envelope of active hip motion in different sporting, recreational, and daily-living activities: A systematic review

Shuyang Han[a], Ryan S. Kim[a], Joshua D. Harris[c], Philip C. Noble[a,b,*]

[a] Institute of Orthopedic Research & Education, Houston, TX, USA
[b] Baylor College of Medicine, Houston, TX, USA
[c] Houston Methodist Orthopedics & Sports Medicine, Houston, TX, USA

A R T I C L E I N F O

Keywords:
Hip motion
Kinematics
Gait
Sports
Activities of daily living

A B S T R A C T

Background: In treating patients with limitations of hip motion, it is generally assumed that correction of bony morphology will provide the patient with the joint motion required to resume their activities. However, the positions of impingement and the specific excursions of joint motion required by each sport may vary. This systematic review aimed to define the envelope of active hip joint motion for participation in different sporting, recreational, and daily-living activities.

Methods: The EMBASE, PubMed, Google Scholar, and Cochrane databases were searched to identify studies that reported kinematics of the hip in sporting, recreational, and daily-living activities. Inclusion criteria were (1) peer-reviewed articles reporting hip kinematics in a certain type of activity, and (2) presented in English. To synthesize the kinematic data, the peak values of kinematic components (i.e. flexion/extension, abduction/adduction, and internal/external rotation) during an activity, as well as the concurrent values in a certain phase of the activity were collected from each study.

Results: A total of 67 studies met the inclusion criteria, involving 32 different types of activities. Seventeen activities required at least one component of supra-physiologic hip motion, however, there were eight different combinations of flexion/extension, abduction/adduction, and internal/external rotation observed. Specifically, three activities (sex, sitting cross-legged, and grand ecart lateral of ballet dancing) required simultaneous extreme degrees of all three components, five activities (arabesque, developpe devant right, and developpe a la seconde right of ballet dancing, picking up something, and taekwondo) required high degrees of two components, most commonly hip abduction combined with flexion or internal rotation.

Significance: This review highlighted that many activities place supraphysiologic demands on hip joint motion, however, the kinematic components affected differ dramatically with the specific activity. This suggests that the demands of each patient's individual activities must be assessed before recommending or planning treatment rather than assuming that a fixed value of “normal” hip motion is applicable to all.

1. Introduction

The osseous and soft tissue structures of the hip joint allow it to have a wide range of motion (ROM), which enables our effective participation in multiple activities, from low demand daily tasks, such as walking and stair climbing to moderate demand motions such as squatting and kneeling, and even to certain sporting activities that have high or extreme demands. For example, hip internal rotation in ice hockey goaltenders appeared close to the end ROM [1]. A normal ROM at the hip joint is of great significance to enable one's ability to effectively perform such activities. However, participating in high demand activities has been proved to be related to various hip problems [2,3], such as increased risk of physeal abnormalities, hip deformity at skeletal maturity, and increased risk for hip osteoarthritis (OA) later in life [4]. Consequently, restricted hip motion and abnormal gait biomechanics were demonstrated for patients with hip dysfunction such as femoroacetabular impingement (FAI), a similar condition that has been linked to OA as a precursor disease. FAI individuals experienced reduced hip abduction, frontal ROM and sagittal ROM during gait [5]. Similarly, motion deficiencies were also common amongst OA patients [6]. Despite the massive amount of studies on hip kinematics during various activities, no study, to our best understanding, has comprehensively analyzed the kinematic demands placed on the hip joint during a wide range of different activities.

* Corresponding author at: Institute of Orthopedic Research & Education, 5420 West Loop South, Suite 3500, Houston, TX, 77401, USA.
E-mail address: pnoble@bcm.edu (P.C. Noble).

https://doi.org/10.1016/j.gaitpost.2019.05.006
Received 11 December 2018; Received in revised form 16 April 2019; Accepted 2 May 2019
0966-6362/

Surgical interventions such as total hip arthroplasty, hip arthroscopy, and FAI corrective surgery have been widely used in the treatment of hip problems with the aim of restoring patient mobility [7]. However, it is worth noting that while treating patients with limitations of hip motion, it is generally assumed that correction of bony morphology will provide the patient with the joint motion required to resume their activities [8]. However, the positions causing impingement and the specific excursions of joint motion required by each sport may vary. Hip positions during each specific activity are a series of combinations of three components in sagittal, transverse, and frontal planes, which are associated with each other, thus it is vital to study the concurrent values of the three kinematic components, rather than merely focusing on any one of them.

Therefore, the purpose of this review was to investigate the active hip ROM during different sporting, recreational, and daily-living activities, thereby analyzing the kinematic demands placed on hip joint during different types of activities.

2. Methodology

2.1. Identification of studies

A review protocol was registered in PROSPERO (CRD42017080488). To identify studies potentially eligible for inclusion, the EMBASE, Medline, Google Scholar, and Cochrane databases were searched by two independent reviewers (SH and RK) from inception until November 2018. The search strategy employed across the electronic databases is presented below:

1 Hip Joint/
2 Lower extremity.ti.ab.
3 Kinematic$.ti,ab.
4 Kinetic$.ti,ab.
5 Range of motion or ROM
6 Motion analysis
7 Hip adj3 biomechanic$
8 1 or 2
9 3 or 4 or 5 or 6 or 7
10 Activit$
11 exp Sports/
12 exp Gait/
13 exp Locomotion
14 walk or stair or run or kneeling or squatting or sitting or hockey or football or soccer or ballet or baseball or basketball or volleyball or taekwondo or golf or landing or side step
15 10 or 11 or 12 or 13 or 14
16 8 and 9
17 15 and 16

Meanwhile, a manual review of the bibliography of articles eligible for inclusion was conducted to identify any additional literature.

2.2. Study screening

Eligible studies were screened by two independent reviewers (SH and RK) according to the inclusion criteria: (1) studies involving healthy subjects, and (2) studies relating to hip kinematics (flexion-extension, abduction/adduction, internal/external rotation) in a certain activity. The exclusion criteria were as follows: (1) cadaveric studies, and (2) kinematic assessment under passive conditions. The title, abstract, and, if necessary, full text were reviewed to identify the studies eligible for inclusion in this review. Duplicate studies were excluded. Disagreements were resolved by a consensus after discussion. A flow chart of the study screening process based on PRISMA recommendations is shown in Fig. 1.

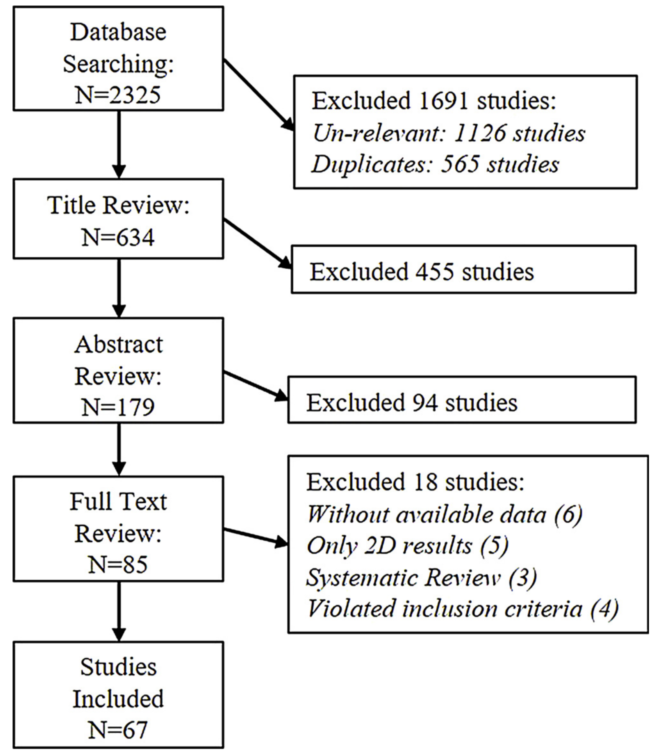

Fig. 1. Flow chart of study inclusion.

2.3. Data abstraction

For eligible studies, data were collected and recorded in two spreadsheets, including general study information (lead author, year of publication, sample size, mean age, gender, measurement method, activity) and hip kinematics (flexion/extension, abduction/adduction, internal/external rotation). The study author was contacted by e-mail if relevant information was not available. If kinematic data was presented in the form of a graph, the values were visually obtained based on the graph axis to best of our ability. Since different conventions were used in reporting hip kinematics, the kinematics data were recorded assuming that hip flexion, abduction, and internal rotation are positive. The spreadsheets are seen in Supplementary Files 1 and 2. It is worth noting that when referring to peak values for any parameter for any activity we are presenting the maximum of the corresponding average peak values from the relevant studies, rather than the maximum of values for individuals.

2.4. Quality assessment

The methodological quality of eligible studies was assessed independently by two reviewers (SH and RK) using a quality assessment tool (Table 1). The maximal score for a study is 14 points. Any disagreement was resolved by a consensus. Further, the overall design of each individual study was identified. If the study was a clinical investigation of patients or athletes receiving interventions, the appropriate clinical study design (e.g. randomized controlled clinical trial, cohort study, case control study, case series, and case report) was assigned. If, however, the study was a laboratory study, it was categorized under descriptive laboratory study or controlled laboratory study. The level of evidence was graded based on the Center for Evidence Based Medicine guidelines [9]. Two reviewers classified the studies individually.

Table 1
Methodological quality assessment.

Criteria	Description	Score = 0	Score = 1	Score = 2
1	Was the aim of the study specified?	Not defined	Inadequately defined	Clearly defined
2	Was subject's demographic information present: age (mean and range, median or SD), gender, and BMI?	Not defined	Inadequately defined	Clearly defined
3	Were subject characteristics reported: type of activity level, sport participation, etc.?	Not defined	Inadequately defined	Clearly defined
4	Were measurement method and instrument described in sufficient detail to permit replication of the test?	Not defined	Inadequately defined	Clearly defined
5	Was data calculation method specified?	Not defined	Inadequately defined	Clearly defined
6	Were the outcome measures reported in all three anatomical planes?	Not defined	Inadequately defined	Clearly defined
7	Was statistical analysis conducted?	Not defined	Inadequately defined	Clearly defined

3. Results

3.1. Search yield

We identified a total of 2325 potentially relevant articles from the initial search. Following title and abstract screening, 85 were identified for full text review. After application of the inclusion criteria, 67 articles were finally adopted. The study inclusion process is shown in Fig. 1.

3.2. Study characteristics

The characteristics and results of the 67 eligible studies are summarized in Supplementary File 1. The included studies were classified in groups according to the type of activity investigated. A total of 32 activities were reported in these studies, namely ballet dancing [2,10,11], basketball [12], chair rising [13], crossing obstacle [14], American football [15], golf swing [16], hockey [1,17–19], kneeling [20–22], shoe tying [7], landing [23–37], lying down on the floor [7], lunging [38], picking up something [7], pitching [39], pivoting [28], running [40–49], sex [50], shuttle run [29], side-step cutting [28,29,46,51–55], single leg jump [47], sitting cross-legged [20,56], skiing [57], soccer [58–60], squatting [13,20,22,38,47,49,61], stair ascent [62–64], stair descent [62,64,65], stand to sit [7], stepping-down [23], stepping-up and –over [38], taekwondo [66], twisting [13], and walking [13,44,49,62,63,67–73]. A total of 2011 subjects (males: 807, females: 1124, unclear: 80 [14,15,60]) were involved.

3.3. Quality assessment

The results of the methodological quality assessment are presented in Supplementary file 3. On the methodological quality assessment scale from 0 to 14, the mean score was 10.6. The type of study design and level of evidence of each study are summarized in Supplementary file 3. Most of the studies (60 out of 67) are laboratory studies, of which 33 are controlled laboratory studies, and 27 are descriptive laboratory studies. The remaining seven studies are clinical studies, with 4 case-control studies (level III), 2 cohort studies (level II) and one case report (level IV).

3.4. Hip kinematics

To assess kinematic outcomes, a variety of technological methods were used in the included studies, including high-speed motion capture systems, electrogoniometric apparatus, electromagnetic tracking systems, inertial systems, model-based image-matching technique, MRI-based assessment, and X-ray detectors. Most studies (59 of 67) adopted high-speed motion capture systems with markers attached to the participants to calculate joint kinematics. Three studies [20,26,38] used electromagnetic tracking systems to collect 3D kinematics, while one other study [1] employed an inertial system (Xsens Mvn Biomech, Xsens Technologies). Since the soft tissue artifacts along with external markers can bring substantial errors, Hara et al. [13] evaluated hip kinematics by a 3D-to-2D Model-to-Image Registration Technique based on continuous X-ray images. The accuracy of 0.3° was equivalent to previous studies. Similarly, a MRI-based assessment [11] and a model-based image-matching technique [57] were used to investigate the hip kinematics in the ballet split motion and alpine skiing, respectively. The earliest study was published in 1969 using an electrogoniometric apparatus [71], the results of which are in good agreement with recent studies [62,67,70].

Of the 67 studies, 20 articles presented sets of all three kinematic components recorded concurrently from 19 activities, 8 studies reported 1 or 2 concurrent components of hip motion. Moreover, the peaks of kinematic components were reported in 52 studies for 25 activities. Therefore, in this study the results are summarized in two ways: (1) peak value of each kinematic component during an activity, and (2) concurrent values of the three components at a certain phase of an activity. It is worth noting that in several studies [10,25,41,46,47,54,57,60,68], since only a graph of hip kinematics was present, visual estimation was made based on the graphs. In two other studies [62,70], data were extracted from the appendix.

Compared to activities of daily livings, higher demand might be placed on the hip joint during sporting and dancing activities, mostly in 2 or 3 components. Three studies [2,10,11] examined the typical motions of ballet dancing in 42 ballet dancers. From these studies, it can be seen that the hip was highly flexed and abducted with large internal or external rotation. The maximal hip flexion angle was 133° obtained during the ballet split position [11], and the hip abduction, internal and external rotation reached as high as 73.10° (grand ecart facial left), 37.90° (right grand ecart lateral right) and 42.00° (grand plie left), respectively. Similar supraphysiologic hip motion was also demonstrated in the transverse plane during ice hockey. Specifically, the hip was internally rotated by 42.30° in butterfly motion, while a peak external rotation of 28.4° was reached in a recovery movement. Activities beyond sports may also require extreme hip positions. One study [50] investigated the kinematics of both male and female hips in 12 common sexual positions. Men exhibited 47° of external rotation while lying on the left side. Table 2 summarizes the peak value of each component of hip motion during 25 activities. It can be seen that three activities (i.e. shoe tying, lying down on the floor, and ballet dancing) require over 120° peak hip flexion. Hip abduction varies from low demand daily activities, such as stair ascent (4.9°), walking (9.18°), and single leg jump (5°) to demanding activities such as soccer (30.0°), side-step cutting (33.1°), sex (35.0°), hockey (35.1°), American football (37.65°), taekwondo (45.1°), and ballet dancing (73.1°). Peak hip adduction was about 5°-10° larger in low demand daily activities such as walking, squatting and landing than in the demanding activities, except for side-step cutting movement (-24°). In terms of hip rotation, peak values of > 30° are demonstrated in both internal and external directions for ballet dancing, golf swing, and hockey. In addition, taekwondo, sex, and sitting cross-legged also require a high degree of hip rotation.

To obtain the envelope of active hip motion during different activities, the concurrent 3D kinematics in a certain phase of an activity, such as initial foot contact, toe off, peak vertical ground reaction force, etc. were integrated. The data points of the same activity were connected to obtain the envelope of hip ROM for each activity, as shown in Figs. 2 and 3. It can be seen that hip ROM is very activity-specific. In the

Table 2
Peak hip joint motion during various activities.

Activity	Flexion	Extension	Abduction	Adduction	Internal Rotation	External Rotation
Ballet Dancing	133.00	−42.80	73.10	0.00	37.90	−42.00
Single leg jump	N/A	N/A	5.00	−5.00	6.00	−5.50
American Football	64.45	−14.72	37.65	N/A	16.92	−13.11
Golf swing	N/A	N/A	N/A	N/A	34.80	−29.70
Hockey	61.70	−20.00	35.10	−10.70	42.30	−28.40
Kneeling	110.50	0.00	26.70	−4.00	12.10	−25.10
Shoe tying	121.00	92.00	14.00	−7.00	10.00	−5.00
Landing	95.00	−9.25	30.10	−21.00	21.60	−14.00
Lying down	130.00	85.00	25.00	−5.00	11.00	−21.00
Lunging	74.20	−9.20	N/A	−13.30	N/A	−19.30
Picking up something	110.00	74.00	21.00	3.00	32.00	−3.00
Running	89.90	−37.67	15.00	−16.00	11.17	−18.00
Sex	108.00	−10.00	35.00	−17.00	17.00	−47.00
Shuttle run	54.70	N/A	27.80	N/A	24.10	N/A
Side-step cutting	54.10	N/A	33.10	−24.00	22.00	−6.50
Sitting cross-legged	101.70	−1.90	34.10	−2.40	11.90	−37.10
Soccer	N/A	−9.30	30.00	−14.80	22.00	6.00
Squatting	121.30	−11.20	29.50	−22.40	18.70	−31.60
Stair ascent	67.07	3.55	4.90	−10.59	5.59	−9.27
Stair descent	39.96	1.60	5.40	−9.40	6.05	−20.20
Stand-to-sit	115.00	80.00	19.00	−2.00	9.00	−14.00
Stepping down	N/A	N/A	N/A	−18.80	5.40	N/A
Stepping up-and-over	51.10	−9.90	N/A	−17.4	N/A	−20.7
Taekwondo	51.00	−10.80	45.10	N/A	34.70	−18.30
Walking	57.50	−19.60	9.18	−21.60	14.90	−12.40

Note: The values presented here are the maximum of the corresponding average peak values from the relevant studies, rather than the maximum of values for individuals.

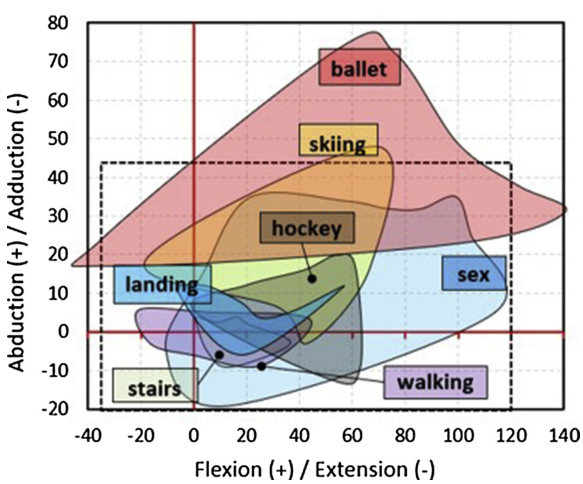

Fig. 2. Envelope of hip motion in the coronal plane during different activities.

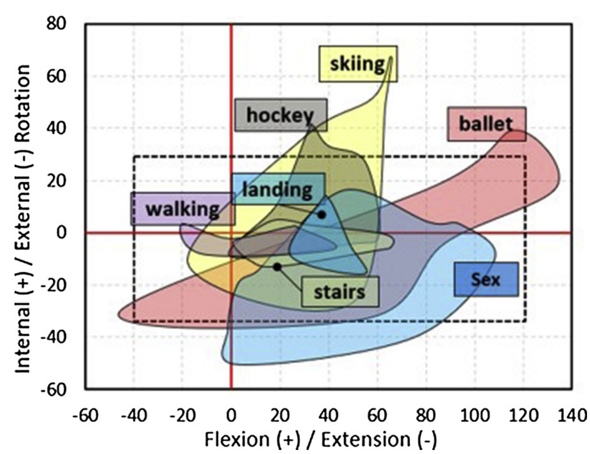

Fig. 3. Envelope of hip motion in the transverse plane during different activities.

coronal plane, large abduction is required during ballet dancing, sex, and skiing. In the transverse plane, ballet dancing demonstrates large hip internal rotation, but not as significant as skiing. In terms of external rotation, three activities (i.e. ballet dancing, sex, and skiing) showed high demands as well.

The kinematic demand placed on the hip joint was graded for each activity and grouped into four categories: low demand (flexion < 50°, abduction < 20°, extension/adduction/rotation < 10°), moderate demand (flexion 50°-90°, abduction 20°-30°, extension/adduction/rotation 10°-20°), high demand (flexion 90°-120°, extension 20°-25°, abduction 30°-45°, adduction/rotation 20°-30°), and extreme demand (flexion > 120°, extension > 25°, abduction > 45°, adduction/rotation > 30°) (Table 3). It turns out that 17 activities, including six ballet dancing positions required at least one component of supraphysiologic hip motion, however, there were eight different combinations of flexion/extension, abduction/adduction, and internal/external rotation. Three activities (i.e. grand ecart lateral of ballet dancing, sex and sitting cross-legged) required high-extreme degrees of all three components, while five activities (i.e. arabesque, developpe devant right, and developpe a la seconde right of ballet dancing, picking up something, and taekwondo) required two, most commonly hip abduction combined with flexion or internal rotation. The remaining nine activities (grand ecart facial and grand plie of ballet dancing, American football, golf swing, hockey, lying down, pitching, skiing, and twisting) required extreme motion in only one direction, most commonly abduction or internal/external rotation.

4. Discussion

The present study explores the 3D hip kinematics required for participation in various daily, sporting, and recreational activities. In general, the results show that daily activities such as walking, running, landing, and stair ascent and descent place low-moderate demands on hip kinematics, whereas sporting, ballet dancing, and some daily-living activities require supraphysiologic hip motion in at least one direction, mostly ab/adduction or internal/external rotation.

Table 3
Kinematic demands placed on the hip during different activities.

Activity		Flexion	Extension	Abduction	Adduction	Internal Rotation	External Rotation
Ballet	Arabesque		high	moderate			high
	Developpe devant right	high		high			low
	Developpe a la seconde right	high		extreme		moderate	
	Grand ecart facial	moderate		extreme		low	low
	Grand ecart lateral	high	extreme	high		extreme	extreme
	Grand plie	moderate		extreme			moderate
American Football		moderate	moderate	high		moderate	moderate
Golf swing						extreme	extreme
Hockey		moderate	moderate	moderate	low	extreme	high
Lying down		extreme		moderate	low	moderate	moderate
Picking up something		high		moderate	low	extreme	low
Pitching		high		low		moderate	
Sex		high		high	moderate	moderate	extreme
Sitting cross-legged		high	low	high	low	moderate	extreme
Skiing		moderate		moderate		extreme	high
Taekwondo		low		extreme		extreme	moderate
Twisting		low		low		extreme	extreme

Although the relationship between high-demanding activity participation (e.g. ballet dancing, hockey, golf, American football, taekwondo and skiing) and the development of joint diseases is not clearly identified, studies have reported a higher risk of developing joint problems (FAI, OA, hip dysplasia, labral pathology, etc.) amongst sport-participating population and ballet dancers. For example, the risk of developing cam-type FAI is up to ten times greater in athletes participating in hockey, basketball, and other jumping sports [4]. It is reported that the labrum is highly compressed during extreme motion of the hip [2], thus high-demand activities are prone to cause labral strain, and tears. Mechanical conflict may also occur between the femoral neck and acetabulum, especially with combined flexion, adduction, and internal rotation. In ice hockey, the butterfly movement of goaltenders requires extreme internal rotation (~40°) combined with flexion [1,19], which ostensibly reveals a potential for impingement. Meanwhile, those 'at-risk' positions (extreme hip flexion/extension, abduction, and internal/external rotation) can severely stress the sacroiliac joint and surrounding soft tissue. Many soft tissue sources of hip pain are found in dancers, including injury involving the iliopsoas, ischiofemoral impingement, and ischial apophysitis. Besides, these activities are often performed repetitively throughout warm-ups, training, and competitive practice drills. Current theories suggest that repetitive movements may also a key factor contributing to hip pain or injury. Repetitive loading results in cumulative excessive micro-damage, increasing the risk for labral tears or osteoarthritis [74,75]. In summary, participating in high-demanding activities is associated with the development of hip pain, injury, or bony deformity.

'At-risk' positions were identified in some daily-living activities as well, such as sitting cross-legged, lying down on the floor, picking up motion, and sexual activity. For example, sitting cross-legged placed extreme demands on the hip with combined flexion (80°-100°), abduction(~30°) and external rotation (~35°) [20,56]. However, it is not well documented whether performing these activities is related to the development of hip problems. Compared to high-level impact sports, these activities involve low kinetic characteristics of the hip joint (e.g. joint moments, velocity, and muscle contribution). Moreover, hip joint loads significantly decreased due to the non-weight bearing conditions of these activities. Therefore, it is plausible that, in addition to joint kinematics, the kinetics during a specific activity also play an essential role in development of joint diseases.

There are some limitations in this review. First, only a small number of eligible studies was identified for some activities (basketball, chair rising, American football, shoe tying, golf), more data are required to better understand the hip kinematics during these activities. Second, there is a large number of studies on the hip kinematics during activities of daily living (e.g. gait, stair ascent and descent, running, etc.), so we are unable to include each individual study. However, the results were not compromised because the data were in good consistency among those studies. Third, only articles written in English were included, which excluded potential studies published locally in a different language. Such studies might be especially important when it comes to an activity that is related to racial, cultural, or religious features.

5. Conclusion

Many sporting and recreational activities place supraphysiologic demands on the hip joint. The kinematic components affected, however, differ dramatically with the specific activity. This suggests that the demands of each patient's individual activities must be assessed before recommending or planning treatment rather than assuming that a fixed value of "normal" hip motion is applicable to all.

Conflict of interest

The authors declare that they have no conflict of interest relating to the material presented in this article.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2019.05.006.

References

[1] D. Whiteside, J.M. Deneweth, A. Bedi, R.F. Zernicke, G.C. Goulet, Femoroacetabular impingement in elite ice hockey goaltenders: etiological implications of on-ice hip mechanics, Am. J. Sport Med. 43 (2015) 1689–1697.
[2] C. Charbonnier, F.C. Kolo, V.B. Duthon, N. Magnenat-Thalmann, C.D. Becker, P. Hoffmeyer, et al., Assessment of congruence and impingement of the hip joint in professional ballet dancers - a motion capture study, Am. J. Sport Med. 39 (2011) 557–566.
[3] M.J. Philippon, C.T. Zehrns, K.K. Briggs, D.J. Manchester, D.A. Kuppersmith, Hip instability in the athlete, Oper. Technol. Sport Med. 15 (2007) 189–194.
[4] J.J. Nepple, J.M. Vigdorchik, J.C. Clohisy, What is the association between sports participation and the development of proximal femoral cam deformity? A systematic review and meta-analysis, Am. J. Sports Med. (2015).
[5] M.J. Kennedy, M. Lamontagne, P.E. Beaule, Femoroacetabular impingement alters hip and pelvic biomechanics during gait: Walking biomechanics of FAI, Gait Posture 30 (2009) 41–44.
[6] K.C. Foucher, B.R. Schlink, N. Shakoor, M.A. Wimmer, Sagittal plane hip motion reversals during walking are associated with disease severity and poorer function in

subjects with hip osteoarthritis, J. Biomech. 45 (2012) 1360–1365.
[7] C. Charbonnier, S. Chague, J. Schmid, F.C. Kolo, M. Bernardoni, P. Christofilopoulos, Analysis of hip range of motion in everyday life: a pilot study, Hip Int. 25 (2015) 82–90.
[8] J.D. Sampson, M.R. Safran, Biomechanical implications of corrective surgery for FAI: an evidence-based review, Sports Med. Arthrosc Rev. 23 (2015) 169–173.
[9] J. Howick, I. Chalmers, P. Glasziou, T. Greenhalgh, C. Heneghan, A. Liberati, et al., The 2011 Oxford CEBM Evidence Levels of Evidence (Introductory Document), Oxford Centre for Evidence-Based Medicine, 2011.
[10] H. Pohjola, M. Sayers, R. Mellifont, D. Mellifont, M. Venojarvi, Three-dimensional analysis of a ballet dancer with ischial tuberosity apophysitis. a case study, J. Sport Sci. Med. 13 (2014) 874–880.
[11] B. Gilles, F.K. Christophe, N. Magnenat-Thalmann, C.D. Becker, S.R. Duc, J. Menetrey, et al., MRI-based assessment of hip joint translations, J. Biomech. 42 (2009) 1201–1205.
[12] M.-S.M. Chan, C. Huang, C. Jia-Hao, T.W. Kernozek, Kinematics and kinetics of the knee and hip position of female basketball players during side-step cutting with and without dribbling, J. Med. Biol. Eng. 29 (2009) 178–183.
[13] D. Hara, Y. Nakashima, S. Hamai, H. Higaki, S. Ikebe, T. Shimoto, et al., Kinematic analysis of healthy hips during weight-bearing activities by 3D-to-2D model-to-image registration technique, Biomed Res. Int. 2014 (2014) 457573.
[14] T.W. Lu, H.L. Chen, S.C. Chen, Comparisons of the lower limb kinematics between young and older adults when crossing obstacles of different heights, Gait Posture 23 (2006) 471–479.
[15] J.M. Deneweth, S.M. Pomeroy, J.R. Russell, S.G. McLean, R.F. Zernicke, A. Bedi, et al., Position-specific hip and knee kinematics in NCAA football athletes, Orthop. J. Sports Med. 2 (2014) 1–10.
[16] H. Gulgin, C. Armstrong, P. Gribble, Weight-bearing hip rotation range of motion in female golfers, N. Am. J. Sports Phys. Ther. 5 (2010) 55–62.
[17] T. Upjohn, R. Turcotte, D.J. Pearsall, J. Loh, Three-dimensional kinematics of the lower limbs during forward ice hockey skating, Sport Biomech. 7 (2008) 206–221.
[18] J.D. Stull, M.J. Philippon, R.F. LaPrade, At-risk" positioning and hip biomechanics of the peewee ice hockey sprint start, Am. J. Sport Med. 39 (2011) 29s–35s.
[19] C.A. Wijdicks, M.J. Philippon, D.M. Civitarese, R.F. LaPrade, A mandated change in goalie pad width has no effect on ice hockey goaltender hip kinematics, Clin. J. Sport Med. 24 (2014) 403–408.
[20] A. Hemmerich, H. Brown, S. Smith, S.S.K. Marthandam, U.P. Wyss, Hip, knee, and ankle kinematics of high range of motion activities of daily living, J. Orthop. Res. 24 (2006) 770–781.
[21] H. Zhou, D.M. Wang, T.R. Liu, X.S. Zeng, C.T. Wang, Kinematics of hip, knee, ankle of the young and elderly Chinese people during kneeling activity, J. Zhejiang Univ.-Sci. B 13 (2012) 831–838.
[22] S.Y. Han, S.R. Ge, H.T. Liu, Gender differences in lower extremity kinematics during high range of motion activities, J. Med. Imag. Health Int. 4 (2014) 272–276.
[23] J.E. Earl, S.K. Monteiro, K.R. Snyder, Differences in lower extremity kinematics between a bilateral drop-vertical jump and a single-leg step-down, J. Orthop. Sports Phys. 37 (2007) 245–252.
[24] C.D. Pollard, S.M. Sigward, S. Ota, K. Langford, C.M. Powers, The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players, Clin. J. Sport Med. 16 (2006) 223–227.
[25] C.H. Yeow, P.V.S. Lee, J.C.H. Goh, Effect of landing height on frontal plane kinematics, kinetics and energy dissipation at lower extremity joints, J. Biomech. 42 (2009) 1967–1973.
[26] N. Cortes, J. Onate, J. Abrantes, L. Gagen, E. Dowling, B. Van Lunen, Effects of gender and foot-landing techniques on lower extremity kinematics during drop-jump landings, J. Appl. Biomech. 23 (2007) 289–299.
[27] J.D. Chappell, R.A. Creighton, C. Giuliani, B. Yu, W.E. Garrett, Kinematics and electromyography of landing preparation in vertical stop-jump - Risks for non-contact anterior cruciate ligament injury, Am. J. Sport Med. 35 (2007) 235–241.
[28] N. Cortes, J. Onate, B. Van Lunen, Pivot task increases knee frontal plane loading compared with sidestep and drop-jump, J. Sport Sci. 29 (2011) 83–92.
[29] S.G. McLean, K.B. Walker, A.J. van den Bogert, Effect of gender on lower extremity kinematics during rapid direction changes: an integrated analysis of three sports movements, J. Sci. Med. Sport 8 (2005) 411–422.
[30] C.D. Pollard, S.M. Sigward, C.M. Powers, Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments, Clin. Biomech. 25 (2010) 142–146.
[31] K.F. Orishimo, I.J. Kremenic, E. Pappas, M. Hagins, M. Liederbach, Comparison of landing biomechanics between male and female professional dancers, Am. J. Sport Med. 37 (2009) 2187–2193.
[32] M. Liederbach, I.J. Kremenic, K.F. Orishimo, E. Pappas, M. Hagins, Comparison of landing biomechanics between male and female dancers and athletes, part 2 influence of fatigue and implications for anterior cruciate ligament injury, Am. J. Sport Med. 42 (2014) 1089–1095.
[33] N.A. Bates, K.R. Ford, G.D. Myer, T.E. Hewett, Kinetic and kinematic differences between first and second landings of a drop vertical jump task: implications for injury risk assessments, Clin. Biomech. 28 (2013) 459–466.
[34] T.W. Kernozek, M.R. Torry, H. Van Hoof, H. Cowley, S. Tanner, Gender differences in frontal and sagittal plane biomechanics during drop landings, Med. Sci. Sports Exerc. 37 (2005) 1003–1012.
[35] R.K. Lawrence, T.W. Kernozek, E.J. Miller, M.R. Torry, P. Reuteman, Influences of hip external rotation strength on knee mechanics during single-leg drop landings in females, Clin. Biomech. 23 (2008) 806–813.
[36] W.A. Laughlin, J.T. Weinhandl, T.W. Kernozek, S.C. Cobb, K.G. Keenan, K.M. O'Connor, The effects of single-leg landing technique on ACL loading, J. Biomech. 44 (2011) 1845–1851.
[37] E. Delahunt, L. Sweeney, M. Chawke, J. Kelleher, K. Murphy, M. Patterson, et al., Lower limb kinematic alterations during drop vertical jumps in female athletes who have undergone anterior cruciate ligament reconstruction, J. Orthop. Res. 30 (2012) 72–78.
[38] M.K. Dwyer, S.N. Boudreau, C.G. Mattacola, T.L. Uhl, C. Lattermann, Comparison of lower extremity kinematics and hip muscle activation during rehabilitation tasks between sexes, J. Athl. Train. 45 (2010) 181–190.
[39] M.D. Milewski, S. Ounpuu, M. Solomito, M. Westwell, C.W. Nissen, Adolescent baseball pitching technique: lower extremity biomechanical analysis, J. Appl. Biomech. 28 (2012) 491–501.
[40] A.G. Schache, P.D. Blanch, D.A. Rath, T.V. Wrigley, R. Starr, K.L. Bennell, A comparison of overground and treadmill running for measuring the three-dimensional kinematics of the lumbo-pelvic-hip complex, Clin. Biomech. 16 (2001) 667–680.
[41] A.G. Schache, P. Blanch, D. Rath, T. Wrigley, K. Bennell, Differences between the sexes in the three-dimensional angular rotations of the lumbo-pelvic-hip complex during treadmill running, J. Sport Sci. 21 (2003) 105–118.
[42] R. Ferber, I.M. Davis, D.S. Williams 3rd, Gender differences in lower extremity mechanics during running, Clin. Biomech. 18 (2003) 350–357.
[43] M. Sakaguchi, H. Ogawa, N. Shimizu, H. Kanehisa, T. Yanai, Y. Kawakami, Gender differences in hip and ankle joint kinematics on knee abduction during running, Eur. J. Sport Sci. 14 (Suppl. 1) (2014) S302–9.
[44] E.S. Chumanov, C. Wall-Scheffler, B.C. Heiderscheit, Gender differences in walking and running on level and inclined surfaces, Clin. Biomech. 23 (2008) 1260–1268.
[45] M.J. Lee, S.L. Reid, B.C. Elliott, D.G. Lloyd, Running biomechanics and lower limb strength associated with prior hamstring injury, Med. Sci. Sports Exerc. 41 (2009) 1942–1951.
[46] S.C. Landry, K.A. McKean, C.L. Hubley-Kozey, W.D. Stanish, K.J. Deluzio, Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated run and crosscut maneuver, Am. J. Sport Med. 35 (2007) 1901–1911.
[47] J.D. Willson, I.S. Davis, Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands, Clin. Biomech. 23 (2008) 203–211.
[48] R. Ferber, I.M. Davis, D.S. Williams, C. Laughton, A comparison of within- and between-day reliability of discrete 3D lower extremity variables in runners, J. Orthop. Res. 20 (2002) 1139–1145.
[49] S.Y. Han, G. Cheng, P. Xu, Three-dimensional lower extremity kinematics of Chinese during activities of daily living, J Back Musculoskelet. 28 (2015) 327–334.
[50] C. Charbonnier, S. Chague, M. Ponzoni, M. Bernardoni, P. Hoffmeyer, Christofilopoulos P. Sexual Activity After Total Hip Arthroplasty: A Motion Capture Study, J. Arthroplasty 29 (2014) 640–647.
[51] C.D. Pollard, S.M. Sigward, C.M. Powers, Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver, Clin. J. Sport Med. 17 (2007) 38–42.
[52] C.D. Pollard, I.M. Davis, J. Hamill, Influence of gender on hip and knee mechanics during a randomly cued cutting maneuver, Clin. Biomech. 19 (2004) 1022–1031.
[53] G. Sanna, K.M. O'Connor, Fatigue-related changes in stance leg mechanics during sidestep cutting maneuvers, Clin. Biomech. 23 (2008) 946–954.
[54] S.C. Landry, K.A. McKean, C.L. Hubley-Kozey, W.D. Stanish, K.J. Deluzio, Neuromuscular and lower limb biomechanical differences exist between male and female elite adolescent soccer players during an unanticipated side-cut maneuver, Am. J. Sport Med. 35 (2007) 1888–1900.
[55] S.G. McLean, S.W. Lipfert, A.J. Van Den Bogert, Effect of gender and defensive opponent on the biomechanics of sidestep cutting, Med. Sci. Sports Exerc. 36 (2004) 1008–1016.
[56] H. Zhou, A.M. Liu, D.M. Wang, X.S. Zeng, S. Wei, C.T. Wang, Kinematics of lower limbs of healthy Chinese people sitting cross-legged, Prosthet. Orthot. Int. 37 (2013) 369–374.
[57] T. Bere, K.M. Mok, H. Koga, T. Krosshaug, L. Nordsletten, R. Bahr, Kinematics of anterior cruciate ligament ruptures in world cup alpine skiing 2 case reports of the slip-catch mechanism, Am. J. Sport Med. 41 (2013) 1067–1073.
[58] R.H. Brophy, S.I. Backus, B.S. Pansy, S. Lyman, R.J. Williams, Lower extremity muscle activation and alignment during the soccer instep and side-foot kicks, J. Orthop. Sports Phys. Ther. 37 (2007) 260–268.
[59] R.H. Brophy, S. Backus, A.P. Kraszewski, B.C. Steele, Y. Ma, D. Osei, et al., Differences between sexes in lower extremity alignment and muscle activation during soccer kick, J. Bone Joint Surg. Am. 92A (2010) 2050–2058.
[60] A. Katis, E. Kellis, Three-dimensional kinematics and ground reaction forces during the instep and outstep soccer kicks in pubertal players, J. Sport Sci. 28 (2010) 1233–1241.
[61] B.L. Zeller, J.L. McCrory, W. Ben Kibler, T.L. Uhl, Differences in kinematics and electromyographic activity between men and women during the single-legged squat, Am. J. Sport Med. 31 (2003) 449–456.
[62] G. Bovi, M. Rabuffetti, P. Mazzoleni, M. Ferrarin, A multiple-task gait analysis approach: kinematic, kinetic and EMG reference data for healthy young and adult subjects, Gait Posture 33 (2011) 6–13.
[63] S. Nadeau, B.J. McFadyen, F. Malouin, Frontal and sagittal plane analyses of the stair climbing task in healthy adults aged over 40 years: what are the challenges compared to level walking? Clin Biomech. 18 (2003) 950–959.
[64] A. Protopapadaki, W.I. Drechsler, M.C. Cramp, F.J. Coutts, O.M. Scott, Hip, knee, ankle kinematics and kinetics during stair ascent and descent in healthy young individuals, Clin Biomech. 22 (2007) 203–210.
[65] O.S. Mian, J.M. Thom, M.V. Narici, V. Baltzopoulos, Kinematics of stair descent in young and older adults and the impact of exercise training, Gait Posture 25 (2007) 9–17.
[66] J.W. Kim, M.S. Kwon, S.S. Yenuga, Y.H. Kwon, The effects of target distance on

pivot hip, trunk, pelvis, and kicking leg kinematics in Taekwondo roundhouse kicks, Sport Biomech. 9 (2010) 98–114.
[67] M.K. Kim, Y.S. Lee, A three-dimensional gait analysis of people with flat arched feet on an ascending slope, J. Phys. Ther. Sci. 26 (2014) 1437–1440.
[68] M.P. Kadaba, H.K. Ramakrishnan, M.E. Wootten, Measurement of lower-extremity kinematics during level walking, J. Orthop. Res. 8 (1990) 383–392.
[69] L. Tepla, M. Prochazkova, S. Zdenek, J. Miroslav, Kinematic analysis of the gait in professional ballet dancers, Acta Gymnica 44 (2014) 85–91.
[70] M.H. Schwartz, A. Rozumalski, J.P. Trost, The effect of walking speed on the gait of typically developing children, J. Biomech. 41 (2008) 1639–1650.
[71] R.C. Johnston, G.L. Smidt, Measurement of hip-joint motion during walking. Evaluation of an electrogoniometric method, J. Bone Joint Surg. Am. 51 (1969) 1082–1094.
[72] K.A. Boyer, G.S. Beaupre, T.P. Andriacchi, Gender differences exist in the hip joint moments of healthy older walkers, J. Biomech. 41 (2008) 3360–3365.
[73] S.Y. Han, The Influence of Walking Speed on Gait Patterns During Upslope Walking, J Med. Imag. Health Int. 5 (2015) 89–92.
[74] S. Han, J.W. Alexander, V.S. Thomas, J. Choi, J.D. Harris, D.B. Doherty, et al., Does capsular laxity lead to microinstability of the native hip? Am. J. Sports Med. 46 (2018) 1315–1323.
[75] A.M. Johannsen, A.W. Behn, K. Shibata, L. Ejnisman, T. Thio, M.R. Safran, The role of anterior capsular laxity in hip microinstability: a novel biomechanical model, Am. J. Sports Med. 47 (5) (2019) 1151–1158 363546519827955.