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Research Article

Use of Inertial Measurement Unit to Assess Knee Kinematics During Activities of Daily Living and Sports-Related Activities: A Narrative Review

Abdulraouf Hassan Alsolmi and Ahmad Hamed Alhamed*

Rehabilitation Department, King Abdulaziz Medical city, Jeddah, Saudi Arabia

***Corresponding Author:** Ahmad Hamed Alhamed, Rehabilitation Department, King Abdulaziz Medical city, Jeddah, Saudi Arabia.

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Abstract

Background: Aberrant knee kinematics are often considered as risk factors for knee injuries, therefore, knee kinematics measurement is essential to correct and prevent knee injuries. As optoelectronic systems are limited to laboratory-setting, inertial sensors units (IMU) appear to be suitable tools for unrestrained joint kinematics measurement.

Objectives: Explore the literature on the concurrent validity and test-retest reliability of IMU for measuring knee kinematics, and the IMU application as outcome measures and feedback tools following knee injuries and/or surgeries.

Major findings: TTwelve articles were included. Seven studies looked at the IMU validity for measuring knee kinematics in healthy participants, one study included individuals with knee disorders. Knee sagittal, coronal, and transverse plane movements were investigated during different activities. Correlations between IMU and standard reference systems ranging from 0.4 to 1. One study reported excellent test-retest reliability of IMU during single leg squatting and landing for knee rotation and valgus (ICC > 0.95). Three studies employed IMUs as outcome measures after knee arthroplasty, anterior cruciate ligament (ACL) reconstruction and rehabilitation, finding insignificant differences between comparators (P > 0.05). One study used IMU as a feedback tool to increase knee angle to reduce ACL risk factors and found significant improvement after the feedback (MD 16.2; 95% CI 11.38 to 21.02).

Conclusion: IMU is valid to measure knee kinematics in healthy individuals. The reliability of IMU knee measurements is still unknown. IMU cannot yet be recommended for use as outcome measures after knee injuries and/or surgeries.

Insufficient evidence support IMU as a feedback tool.

Keywords: Knee Joint; Kinematics; Inertial Sensors; Ambulatory Monitoring; Motion Analysis

Abbreviations

The knee joint has a high incidence of injury in both sedentary and active populations,with estimation of 23.2% and 22.3%, in male and female, respectively [1]. Anterior cruciate ligament (ACL) injuries are reported to be one of the most serious knee injuries with 100,000 annual injuries in the United States and, at the same time, gender-specific (female: male - 3:1) in sports such as soccer and basketball [2,3]. Additionally, knee osteoarthritis is a highly prevalent condition and may be treated with knee arthroplasty in the later stages of the condition [4-6]. Knee kinematics are often assessed during various tasks, such as walking or stair navigation, in patients with knee disorders to determine the influence of the injury on function and also to determine outcomes of managements [4,7-9].

Three dimensional (3-D) joint kinematic measurements are valuable as these improve understanding of movements pattern, to detect movement adaptations and toassess and guide treatment decision-

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making and rehabilitation [10]. Motion analysis systems such as video-based optoelectronic systems can obtain accurate 3-D knee kinematics measurements during different activities [11,12]. However, there are several limitations in the optoelectronic systems, including high financial cost, complexity,time consuming, limitation to laboratory setting, and the requirement of specializedstaff [13].

Recently, a new technology has emerged and showed to be a potential alternative to the stationary laboratory-based motion systems. This new system is an inertial measurement unit (IMU), which consists of an accelerometer and a gyroscope [14]. Magnetometer may be combined with accelerometer and gyroscope to improve the accuracy of some of these systems [15]. The IMU was found to be the most commonly utilized wearable sensors for measuring gait kinematics [16], and this might be because of its portability and relative low cost when compared to laboratory-based systems.[14] The IMUs have been used to measure knee kinematics in healthy people [13,17-22]. individuals with knee osteoarthritis [23], as outcome measures after knee surgeries [23,24]. and as a feedback tool to reduce risk factors of ACL injuries [7]. A previous systematic review aimed to explore the validity of IMUs for human movements measurements found that IMUs can provide accurate measurements with the level of accuracy dependent on the site and the performed task [25]. Another narrative review has explored the application of IMUs in human lower extremities biomechanics, and provided general information about IMUs usages and validity [14]. However, these reviews did not provide sufficient information or included only few studies about the validity, reliability, and usefulness of this system for knee joint measurements [14,25].

Therefore, the aim of this narrative review is to assess and synthesize theliterature of using IMUs in monitoring knee joint kinematics. This will validity, reliability, their usability for assessing risks of knee injuries, and their clinical application as feedback tool and outcome measures following knee injuries orsurgeries.

Methods

Articles were included if they were prospective, retrospective, randomized controlled trials, case series, or review articles published from 2005 to 2016, and included men and women with or without knee joint disorders (overuse injuries, acute injuries or osteoarthritis) or surgeries. The studies had to include IMUs consisting of 3-D accelerometers and 3-D gyroscopes, with or without magnetometers. Outcomes of interest were knee joint kinematics including knee angles, stance phase time, swing phase time, and stride length. Studies focusing on the technical and calibration aspectsof IMUs, investigating balance and fall risks, utilizing only one IMU on the back or foot, or involving people with lower limb amputation or neurological disorders were excluded.

Search strategy

An electronic literature search was conducted for articles published in English from 1 January 2005 to 17 March 2016 using six databases: CINAHL, MEDLINE, Pubmed, Scopus, SPORTDiscus, and Web of science. Different MeSH terms or keywords werecombined using Boolean operators (AND, OR) to retrieve potential studies from the electronic databases (Table 1). EndNote X7 software (EndNote X7.5.1 [Bld 11194]) was used to extract, store, and screen the titles and abstracts of articles retrieved from the databases.

Study selection

The primary author independently screened all the titles and abstracts of retrievedarticles for relevance. Thereafter, full-text of potentially relevant studies were obtained and screened for eligibility according to the aforementioned eligibility criteria by the same reviewer.

Studies categorization

Studies included were categorized into validity, reliability, outcome-based, and feedback studies. This categorization was formulated according to objectives of the included studies. Studies comparing the measurement accuracy of IMUs with other reference systems, or comparing the knee range of motion (ROM) between IMUs andstandard systems were included under the validity category. Under the reliability category, studies investigating the test-retest reliability of the knee kinematics were included. Studies using IMUs to quantify outcomes of knee-related surgeries and/or rehabilitation programs were classified under the outcome category. The feedback category included studies utilizing IMUs as a feedback tool to guide rehabilitation exercises. If studies reporting, for example, information related to reliability and outcome, these studies were included into the two categories of relevance.

Data extraction and analysis

Data extracted from each study included citation details, study population and their characteristics, sample size, IMU characteristics, number and placement of IMUs, reference system, functional activity, kinematics variables, statistical measures and study findings. Mean differences (MD) and 95% confidence intervals (95% CI) werecalculated between healthy and patient groups, pre- and post-surgery in single group, two different interventions, and/or pre- and post-feedback sessions using an Excel spreadsheet (Microsoft® Excel® for Mac 2011 Version 14.6.1 [160122]) [26]. MD and95% IC were calculated in validity, outcome-based, and feedback studies.

Body part	Tool/device	Activity	Measurement
“Lower limb”	“Inertial sensors”	ADL	Kinematic
“Lower extremity”		Walking	“Range of motion”
Knee		Running	Angle
“Anterior cruciate ligament”		Jogging	ROM
		“Stair ascent”	“Range of movement”
		“Stair descent”	Analysis
		Jumping	“Joint angular kinematic”
		Gait	“Joint angle”
		Squat	Monitoring
		Movement	
		“Stair climbing”	
		Motion	
		Locomotion	
		Ambulation	
		“Stair negotiation”	
		Exercise	
		Rehabilitation	

Table 1: Keywords/terms used for electronic databases search.

Results

Literature search and screening process

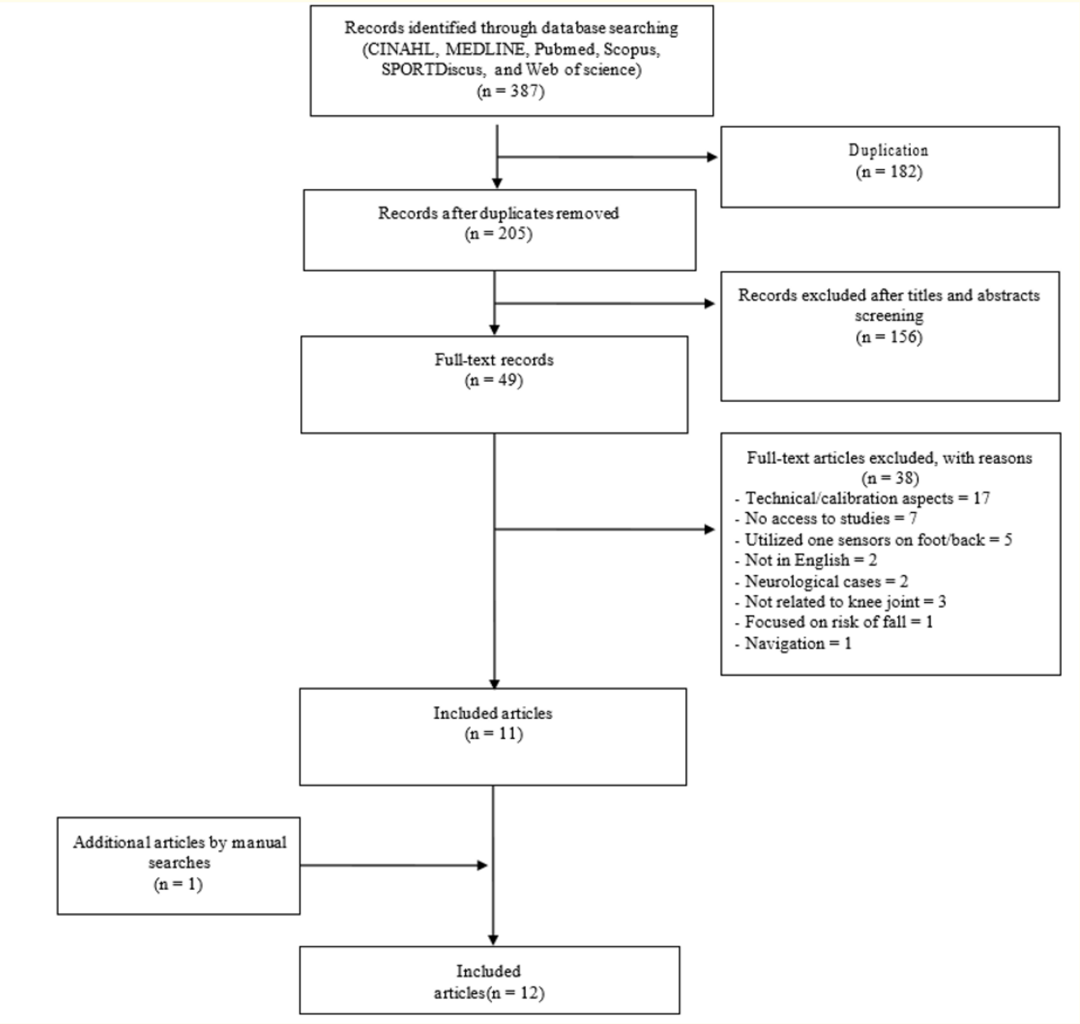
The process of the search strategy and screening of articles that was followed in the current review is shown in figure 1. The electronic databases search retrieved 378 articles. After excluding 182 duplicates, a critical screening of the titles and abstracts of 205 studies using the pre-determined eligibility criteria resulted in 49 articles. Full-text screening of all relevant articles yielded 11 articles that satisfied the eligibility criteria [7,11,13,18-24,27]. Further, manual searches of the references of included articles identified one more relevant study [17].

Concurrent validity of IMU

Eight studies explored the validity of IMUs (Table 2) [11,13,17-21,27]. Of those studies, seven articles recruited healthy participants [11,13,17-21]. One study included both healthy and individuals with different knee problems without reporting detailed information about them [27]. While seven studies included young adults [11,13,17-21], one study did not state the age of participants [27]. IMUs compromised of accelerometers and gyroscopes were used in five studies [13,17,18,20,21]. Only one study utilized magnetometer in combination with accelerometer and gyroscope [27]. In two studies, the characteristics of IMUs were not sufficiently reported [11,19]. Different reference standard systems were used as reported in table 2. The investigated functional activities include over-groundwalking [11,13,17,20,21,27], treadmill walking [18,21]. ascending stairs [19], and descending stairs [11]. Knee sagittal plane movements were of interest in eight studies [11,13,17-21,27], and coronal and transverse planes movements were investigated in two studies [11,13]. Six studies reported correlation coefficient (r) [13,17,19-21,27], while one study reported correlation of multiple coefficient (CMC) [11]. Seven studies reported root mean square error (RMSE) [13,17-21,27]. The overall findings of r-values were ranged from strong to perfect [13], CMC ranged from weak to perfect, and RMSE ranged from 0.7 [18] to 6.8 [17].

Absolute measure of knee angles and the calculated MDs with 95% CIs betweenIMUs and the reference standard systems are presented in table 2.

The studies investigating the validity of IMUs were heterogeneous in nature because of the following factors: different systems were used as a reference standard,variability in the placement and fixation of IMUs, and inadequate statistical analyses.In regard to the statistical analyses, some studies did not mention which type of correlation coefficient was used. Additionally, most of the studies recruited a very small sample sizes which increases the chances of type II error. Therefore, direct comparisons between studies are limited owing to the aforementioned issues.



Graph 1: Flow diagram depicting search strategy and articles selection process.

References	Participants characteristics	IMU placements	IMU characteristics	Reference systems	Activity/task	Validity/ accuracyin movement planes Mean ± SD	ROM by IMUs and ref. systems (°)[a],	MD between IMUs and ref.systems(°)[b]
Favre., *et al.* [13]	N: 10 (M) Age: 29 years (range 32-40) Condition: healthy	One IMU on the lateral aspect of the thigh and one IMU on the medial aspect of the shank, fixed with elastic straps	2 IMUs each consisting of a3D accelerometerand a 3D gyroscope	A Liberty magnetic tracking device	Over-ground walking for 10 seconds	Sagittal planer: 1 ± 0.00 RMSE (°): 1.5 ± 0.4 Coronal planer: 0.8 ± 0.1 RMSE (°): 1.7 ± 0.5 Transverse planer: 0.9 ± 0.0 RMSE (°): 1.6 ± 0.5	-	-

Bergmann., *et al.* [19]	N: 14 (9 M, 5F) Age: 27 years (range 20-37) Condition:healthy	IMUs were placed on both lower extremities. One IMU on each forefoot,one IMU on the medial aspect of each shank, and one IMUon the lateral aspect of each thigh, fixed with double-sided adhesive tapeand additional elastic straps	6 IMUs	Active Coda-motion	Stair ascentat a comfortable pace	Sagittal planer: 0.9 ± 0.1. RMSE (°): 4 ± 3	IMUs:91 ± 8 Ref. system:92 ± 6	1 (-4.5 to 6.5)
Cooper., *et al.* [18]	N: 7 (5 M, 2 F) Age: 30 ± 6 years Condition:healthy	One IMU on the lateral aspect of the thigh and one IMU on the lateral aspectof the shank	2 IMUs with each one consisting of a3D accelerometer (75g) and a 3D gyroscope (71200 deg/s)	10 cameras Qualysis system	Treadmill walking at different speeds	-		-
					1 mph	Sagittal plane RMSE (°): 0.7 ± 0.2		
					2 mph	Sagittal plane RMSE (°): 0.8 ± 0.3		
					3 mph	Sagittal plane RMSE (°): 1.0 ±0.4		
					4 mph	Sagittal plane RMSE (°): 2.3 ±0.6		
					5 mph	Sagittal plane RMSE (°): 3.4 ±1.1		

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Takeda., *etal.* [17]	N: 3 (M) Mean age: 24.7± 2.9 years(mean ± SD) Condition:healthy	IMUs were placed on both lower extremities. One IMU onthe later aspect of each thigh and one IMU on the lateral aspect of each shanks	4 IMUs with each one consisting of a3D accelerometer and a 3D gyroscope	DIPP- Motion Prosystem	Over-ground walking for 5 meters at a cadence of 88 steps/min	Sagittal planer: 0.9 RMSE (°): 6.8	-	-
Watanabe., *et al.* [20]	N: 3 (M)	IMUs on both lower	7 IMUs with each consisting	OPTOTRAK system	Over-ground walking		-	-
		each shank, one IMU on the anterior aspect of each thigh, and one sensor on thelumbar spine,fixed with stretchable bands with hook and loop fastener			walking -Slow (1km/h) -Normal (3km/h) -Fast (5km/h)	r: between 0.9 and1 RMSE (°): between 5 and 6		
Schulze *etal.* [27]	N: 10 Condition: 5 healthy, 5 with different knee problems.	One IMU on the lateral aspect of the thigh and one IMU on the medial aspect of the shank, fixed with kinesiotape.	2 IMUs with each one consisting of a3D accelerometer,a 3D gyroscope, anda 3D magnetometer	8 infrared cameras	Over-ground walking at different speeds estimated by subjects Slow Comfortable	-	-	
						Sagittal planer: 0.99 RMSE (°): 2.2 Sagittal planer: 0.99 RMSE (°): 2.9		
					Fast	Sagittal plane r: 0.98 RMSE (°): 3.1		
Zhang *et* *al.*[11]	N: 10 (5 M, 5 F)	IMUs were placed	Xsens MVN BIOMECH	NDI Optotrak	Over-ground walking	Sagittal plane CMC: 0.99	ROM mD: 0.8	0.8 (-1.1 to 2.7)
		according to	system	3020 system			ROM	
	Age: 24 ± 4	the	consisting of				mE: 1.8	
	years	manufacturer	3D sensors					
		configuration,						

	Condition: healthy	except for IMUs on the shank which were placed on the lateral aspect				Coronal plane CMC: 0.71	ROM mD: 1.5 ROM mE: 5.1	1.5 (-3.6 to 6.5)	
						Transverse plane CMC: 0.88	ROM mD: 0.03 ROM mE: 2.7	0.03 (-2.7 to 2.7)	
					Stair ascent	Sagittal plane CMC: between 0.9 and 1	ROM mD: 0.1 ROM mE: 1.7	0.1 (-1.6 to 1.8)	
					Stair descent	Coronal plane CMC: between 0.4 and 0.6	ROM mD: 0.8ROM mE: 4.7	0.8 (-3.9 to 5.5)	
						Transverse planeCMC: between 0.6 and 0.8	ROM mD: 1.7ROM mE: 5.2	1.7 (-3.5 to 6.8)	
						Sagittal plane CMC: between 1.9 and 1	ROM mD: 0.4ROM mE: 1.9	0.4 (-1.9 to 2.4)	
						Coronal plane CMC: between 0.6 and 0.7	ROM mD: 0.7ROM mE: 5.5	0.7 (-4.9 to 6.2)	
						Transverse planeCMC: between 0.7and 0.8	ROM mD: 0.1 ROM mE: 3.7	0.1 (-3.6 to 3.8)	

Table 2: Studies comparing IMUs to standard motion analysis systems.

Abbreviations: N: Number; M: Male; F: Female; 3D: Three Dimensional; r: Correlation Coefficient; RMSE: Root Mean Square Error; SD: Standard Deviation; mph: Mile Per Hour; CMC: Coefficient of Multiple Correlation; min: Minute; km/h: Kilometer Per Hour; ROM: Range of Motion; IMU: Inertial Measurement Unit; ref: Reference; ROM Md: Mean Differences in Range of Motion Between Two Systems; ROM mE: Grand Mean Error Between Two Systems; MD: Mean Difference

a Values expressed as mean ± standard deviation.

b Values expressed as as mean (95% confidence intervals).

c List of IMUs and reference systems manufacturers are presented in Appendix A.

Reliability study

One study was retrieved that investigated the test-retest reliability of IMUs measurements [22]. This study recruited 29 asymptomatic participants with increased knee valgus and femoral internal rotation, however, different participants number were reported in different sections in the study. The characteristics of the used IMUswere not stated. Intraclass correlation coefficients (ICC) of knee rotation and valgus measurements were excellent in single leg squatting and landing, with standardized error of measurements (SEM) ranging from 3.3° to 4.2°, and minimal detectable change (MDC) ranging from 5° to 5.6°.

Outcome-based and feedback studies

Three studies used IMUs as an outcome measure (Table 3) [22-24]. Following anterior cruciate ligament reconstruction (ACL-R) [24], total knee arthroplasty [23], while the other study used IMUs to investigate the effectiveness of specific rehabilitation programs aimed to reduce risk factors of knee injuries [22]. Two studies recruited young participants [22,24], while one study included older participants [23]. IMUs consisted of accelerometers and gyroscopes used in one study [24], one study utilized IMUs consisted of accelerometer, gyroscope, and magnetometer [23], while the IMUs characteristics were not stated in one study [22]. Different activities and knee kinematics variables wereinvestigated, with no significant differences between comparators identified, as shown in table 3.

One study examined the effectiveness of IMUs for feedback purposes [7]. Thestudy population was young participants with high risk factors of ACL injury. The kinematics variable, of interest in this review, was the magnitude of knee flexion angle during drop jump. The employed IMUs consisted of an accelerometer and a gyroscope to provide visual feedback, and the intervention resulted in a mean increasefor knee flexion angle when landing of 16° (MD 16.2°; 95% CI 11.4 to 21.0).

References	Participants characteristics	IMU placements	IMU characteristics	Activity	Kinematicvariables	Outcomes Mean ± SD	P value	Mean differences^{a}Mean (95%CI)
Calliess et al.[23]	N: 6 (3 M, 3 F) Age: 60.2 ± 5.8 years Experiment: examination of knee variables before and 12-month after knee replacement	One IMU on the lumbosacral junction, oneIMU on the lateral aspectof the thigh, and one IMUon the medialaspect of the shank, fixed with elastic therapeutic tape	3 IMUs with each one consisting of a3D accelerometer, a 3D gyroscope, and a 3D magnetometer	100 meters walk at self- selectednormal speed 50 meters run as fast as possible Four stairs upand down.	Step length(m) Ascending: -Time per stair step (s)	Pre-op: 0.65 ± 0.1 m Post-op: 0.72 ± m Pre-op: 0.59 ± 0.09 s Post-op: 0.55 ± s	Not reported	0.07 (-0.05 to 0.19) -0.04 (-0.16 to 0.08)
					-max. knee Flx (°)	Pre-op: 77.2 ± 15.3 ° Post-op: 78.8 ± 5.6 °		1.7 (-13.2 to 16.5)
					Descending: -Time per stair step (s)	Pre-op: 0.55 ± 0.06 s Post-op: 0.48 ± 0.07 s		-0.07 (-0.15 to 0.01)
					-max. knee Flx (°)	Pre-op: 74 ± 21.6 ° Post-op: 76.3 ± 6.8 °		2.3 (-18.3 to 22.9)
					-Knee Flx at HS (°)	Pre-op: 14.3 ± 8.4 ° Post-op: 22.3 ± 5.6 °		8 (-1.2 to 17.2)

Patterson et al.[24]	N: 31 (F) Groups: -ACL-R: 17 lower limbs of14 female athletes.	IMUs were placed on both lower extremities. One IMU on the anterior aspect of eachshank, fixed	2 IMUs with each one consisting of a3D accelerometer and a 3D gyroscope	Walking15 meters with barefootat self- selected normal	Stance time(s)	ACL-R: 0.57 ± 0.05 s CN: 0.54 ± 0.03 s	0.06	-0.03 (-0.05 to 0.00)
					Swing time(s)	ACL-R: 0.44 ± 0.04 s CN: 0.43 ± 0.03 s	0.77	-0.01 (-0.03 to 0.02)
	Age: 23.7 ± years. Time since surgery: 3.5 ± years. -CN: 17 healthy female athletes. Age: 20.8 ± 1.17 years	with double sided tape andathletic tape		speed				
Palmer et	N: 29 (21 M, 9	One IMU on	2 IMUs	Single	AbdStr:			
al.[22]	F)	the lateral		leg	Flexion (°)	Wk 0: 58.7 ± 8.1 °	Not reported	4.2 (-2.1 to
		aspect of the		squat		Wk 5: 62.9 ± 8.8 °		10.5)
	Condition:	thigh and one						
	healthy with	IMU on the						
	increased knee	lateral aspect			Rotation (°)	Wk 0: -15.2 ± 22.5	0.61	17.8 (-0.9 to
	valgus and	of the shank,				°		36.5)
	femoral	fixed with				Wk 5: 2.6 ± 27.2 °		
	internal	double-sided						
	rotation.	tape and						
		elastic wrap			Valgus (°)	Wk 0: -19.4 ± 19.8	0.61	5.6 (-10.8 to
	Groups:					°		22.0)
	-AbdStr: N: 15					Wk 5: -13.8 ± 23.9		
	(11 M, 4 F)					°		

Age 30.3 ± 8.8 years	Single leg landing	MotCon: Flexion (°)	Wk 0: 58.0 ± 8.1 ° Wk 5: 57.1 ± 7.6 °	Not reported	-0.9 (-7.0 to 5.2)
-MotCon: N: 14 (10 M, 5 F)		Rotation (°)	Wk 0: -16.2 ± 17.0 ° Wk 5: -7.1 ± 13.4 °	0.09	9.1 (-2.8 to 20.9)
Age 29.6 ± 9.7 years		Valgus (°)	Wk 0: -16.2 ± 10.2 ° Wk 5: -6.2 ± 19.8 °	0.12	10 (-2.2 to 22.2)
		AbdStr: Flexion (°)	Wk 0: 51.9 ± 10.0 ° Wk 5: 56.6 ± 11.7 °	Not reported	4.7 (-3.4 to 12.8)
		Rotation (°)	Wk 0: -10.8 ± 11.8 ° Wk 5: -6.5 ± 11.3 °	0.79	4.3 (-4.3 to 12.9)
		Valgus (°)MotCon:	Wk 0: -9.8 ± 11.9 ° Wk 5: -8.9 ± 10.6 °	0.55	0.9 (-7.5 to 9.3)
		Flexion (°)	Wk 0: 48.1 ± 8.5 ° Wk 5: 48.8 ± 10.4 °	Not reported	0.7 (-6.7 to 8.1)
		Rotation (°)	Wk 0: -5.2 ± 9.2 ° Wk 5: -4.8 ± 10.2 °	0.36	0.4 (-7.5 to 7.9)
		Valgus (°)	Wk 0: -5.2 ± 9.6 ° Wk 5: -3.6 ± 12.3 °	0.18	1.6 (-6.9 to 10.2)

Table 3: Studies using IMUs as an outcome measure.

Abbreviations: N (number), M (male), F (female), IMU (inertial measurement unit), 3D (three dimension), ACL-R (anterior cruciate reconstruction group), s (second), SD (standard deviation), CN (healthy/control group), CI (confidence intervals), pre-op (pre operation), post-op (post operation), m (meter), max. (maximum), Flx (flexion), HS(heel strike), AbdStr (abductor strength group), MotCon (motor control group), Wk (week).

[a] List of IMUs manufacturers are presented in Appendix A

Discussion

The objectives of this review were to explore the literature related to the validity and reliability of using IMUs to measure knee kinematics, and their application as outcome measures and/or feedback tools after knee surgeries and/or injuries. Based on the results of this review, IMUs may provide accurate knee kinematics measurements with acceptable errors in healthy participants. However, this accuracy is dependent on the task and the speed at which the task is performed. One study with methodological issues showed excellent reliability for IMUs to measure knee valgus and rotation during single leg squatting and landing in asymptomatic participants. Thestudies that have used IMUs as an outcome measure showed insignificant differences between comparator groups, this might indicate the insufficient sensitivity of IMUs todetect differences, therefore, inappropriateness to be utilized as an outcome measure. One study showed that IMUs might be used as a feedback tool for ACL-injury prevention programs, however, the benefit of using IMU as a feedback tool need further investigations.

Concurrent validity of IMU

Over-ground and treadmill walking

The validity of IMUs was determined by comparing their results to those with standard three-dimensional movement analysis systems. The r-values for sagittal plane knee movements during over-ground walking ranged from 0.92 [17] to 1.00 [13]. However, root mean square error for this plane ranged from 1.5°[13] to 6.7° [17] and thesediscrepancies could be due to differences in the reference systems, calibration methods, and/or variations in IMU placements used in these studies (Table 2).

Moreover, measurement errors associated with the IMUs were found to increase with increasing walking speed [20,27]. In addition, r-values for coronal and transverse planes movements have been found to be 0.86 and 0.95 respectively [13]. The reported errors ranged from 1.7° (for coronal plane movements) to 1.6° (for transverse plane movements) [13]. Zhang., *et al.* [11]. reported CMC of sagittal, coronal, and transverse planesmovements to be 0.99, 0.71, and 0.88 respectively.

For treadmill walking, only sagittal plane movements were investigated [18,21]. Watanabe., *et al.* [21]. stated high r-values ranging from 0.9 to 1.0 for walking at differentspeeds from 1 to 5 km/h. However, the reported value was an average of the r-values of different speeds that were investigated. The accuracy of IMUs also seems to be inconsistent for treadmill walking owing to greater errors occurring with an increase in walking speed [18,21]. Watanabe., *et al.* [21]. reported greatest errors (RMSE) between 5°and 6° for knee flexion. In this study, the RMSE was an average of measurement errors of different walking speeds ranging from 1 to 5 km/h. In contrast, Cooper., *et al.* [18] reported a lower RMSE of 2.3° during a walking speed of 6.4 km/h. High measurement errors reported by Watanabe., *et al.* [21] might be attributed to the IMUs placements in their study (Table 2).

Stair ascent and descent

Bergmann., *et al.* [19] found that IMUs are valid to measure knee sagittal plane movements, with a Pearson correlation coefficient of 0.98 during stair ascent. In line with this study, Zhang., *et al.* [11] reported a high correlation between IMUs and standardsystem in measuring knee sagittal plane angles (CMC values: 0.9-1). RMSE for sagittal plane movements was 4° [19]. Additionally, the CMC of knee angles on the frontal plane was between 0.4 and 0.6, while it was between 0.6 and 0.8 for movements on transverse plane [11]. Zhang., *et al.* [11]. examined the validity of IMUs for frontal and transverse planes movements during the descent of stairs and reported CMC ranging between 0.6 and 0.7 for frontal plane, and 0.7 and 0.8 for transverse plane.

Zhang., *et al.* [11] found that the transverse and coronal planes CMC during the three different activities ranged from 0.4 to 0.88. The reported low values were statedto be potentially due to the need for different calibration methods for IMUs and the reference standard systems.

Absolute measure of knee angles and the calculated MDs with 95% CIs between IMUs and the reference standard systems are presented in table 2. The results indicate that IMUs are able to reproduce knee angles measured by the reference standard systems, used in both studies during over-ground walking and thestair ascent and descent [11,19]. However, differences of up to 1° [19], 1.5°[11], and 1.7°[11] between these systems were reported during the three activities for sagittal, coronal,and transverse planes movements.

Reliability of IMU measurements

A study investigated the test-retest reliability of knee valgus and rotation, as measuredwith IMUs, in 29 healthy military personnel who were assigned into two groups, as part of a study exploring effects of abductor-strengthening exercises and motion- control exercises on those variables [22]. Knee valgus and rotation were measured duringsingle leg squatting and landing. ICCs for both groups were found to be greater than 0.95 for knee valgus and rotation. SEMs were for knee valgus (3.3° to 3.8°) and rotation (3.8° to 4.2°). MDCs were for valgus (5° to 5.3°) and rotation (5.4° to 5.6°). The MDC indicates that it is likely that differences between two measures for rotationor valgus are meaningful only if they are larger than 5°.

In the study, it was not reported in which task, single leg squatting or landing, was the test-retest reliability determined, and whether the test-retest reliabilities were measured across trials in a single occasion or during different occasions. Furthermore,it was not stated which formula was used to estimate MDCs. Therefore, this formula ($1.96 \times \sqrt{2} \times \text{SEM}$) has been used in the current review to calculate the MDCs.

Different MDCs were found, in the abductor strengthening group for knee valgus androtation were 10.5° and 11.6°, respectively. While in the motion control group knee valgus and rotation MDCs were 9.1° and 10.5°, respectively.

The highest mean knee rotation in both groups of the study was 16.2°, and thehighest mean knee valgus was 19.4° (Table 3). By comparing the SEMs and with the means of knee rotation and valgus, the MDC scores for rotation and valgusare large. Therefore, it would be difficult to determine the true changes in these twovariables during single leg squatting and landing in the study population.

IMU as an outcome measure

Patterson., *et al.* [24] investigated gait patterns after ACL-R. The study populations were14 female athletes with ACL-R and 17 healthy female athletes. Of the reported parameters, stance and swing phase time during barefoot walking at self-selected speed were of interest for this review. No differences were found between groups forstance phase duration (MD -0.03 s; 95% CI -0.05 to 0) and swing phase time (MD - 0.004 s; 95% CI -0.03 to 0.02). Stance and swing phases times were concurrently measured by CODA Motion Analysis System and two AMTI force plates in the study. No significant differences between the two groups in the two variables were found, which confirm the findings of IMUs. Overall, these findings indicate that IMUs may not be sufficiently sensitive to determine between group differences in temporal variables during the walking gait when comparing participants with ACL-Rand controls, if such differences exist.

Previously, it was reported that there is a significant difference in knee rotation between healthy individuals compared to ACL injured individuals during single leg squatting [28]. Male participants with ACL-deficient knees exhibited less kneeexternal rotation (mean angle 1.6°) than healthy participants (mean angle 38.8°) during single leg squatting on the affected lower limb. This difference was found to be equal to 37.2°. Therefore, by comparing this difference value to the aforementioned reported SEMs (3.8° to 4.2°) [22] and the calculated MDCs (10.5° to 11.6°) of knee rotation by IMU, the comparisons indicate that IMU might be able todetect true changes in knee rotation during single leg squatting in male individuals with ACL tear. However, the ability of IMU to detect the knee rotation changes during single leg squatting after ACL injury and/or surgery still needs confirmation.

Calliess., *et al.* [23] compared the functional ability of six participants before and 12-month after total knee replacement. The variables that were chosen in the currentreview were step length during walking, time per stairs step, maximum knee flexion,and knee flexion at heel contact during stair ambulation. It was found that all of the included variables did not change significantly between pre- and post-surgery (Table3). It is possible that the insignificant changes in the knee kinematics variables are owing to the study small sample size, which might lead to Type II error. Another possible reason is that there appears to be a large amount of individual variability as shown in table 3. Even so, it is still unknown whether IMUs can be used as an outcome measure after knee arthroplasty or not.

IMUs were used to measure the outcome of two rehabilitation programs aimedto decrease dynamic knee valgus and internal rotation (DKVIR) [22]. The study population consisted of 29 military personnel with increased knee valgus and femoral rotation, different participants numbers were reported throughout the study. Participants were allocated into hip abductors strengthening group or motor controlgroup to determine the effectiveness of these programs to improve DKVIR. Knee flexion, rotation and valgus were examined during single leg squatting and landingbefore and five-week after commencing the exercise protocols. There were no significant changes in any of the variables in both groups between pre- and post-intervention (Table 3). The width of the 95% CIs, as shown in table 3, indicate the presence of large individual variability when using IMUs, thus this might explain the insignificant findings. Additionally, the large values of MDC for knee rotation and valgus during single leg squatting and landing indicate the limited usefulness of IMUsto measure these knee variables during these activity tasks. The large MDCs were determined by comparing the MDC values for knee rotation (10.5° to 11.6°) and valgus (9.1° to 10.5°) to means knee rotation and valgus in both groups (Table 3).

IMU as a feedback tool

Dowling., *et al.* [7] examined the effectiveness of IMUs as a feedback tool to improve lower limb alignment during drop jump. The study investigated whether visual feedback provided by IMUs was able to change kinematic variables that are considered to be associated with ACL injury. The study included 17 healthy individuals involved in recreational sports activities. The chosen variables were knee flexion angle, trunk lean, and coronal thigh angular velocity during drop jump. As theaim of the current review is to explore the utilization of IMUs for the knee joint, kneeflexion angle data was included from this study. Participants performed a baseline drop jump test (without feedback), followed by a training session consisting of 15 to 20 jumps (with visual feedback from IMUs) and an evaluation session (without feedback). Participants were provided with standardized set of movement modification instructions during the training session and visual IMUs feedback showing the lower risk range of knee flexion. The ranges of knee flexion between 88°to 120° were chosen to be the range of the lower risk, and participants were instructedto flexed their knees to be within this range during the drop jump. Nine participants were outside the low risk range of knee flexion during the baseline test, however, these nine participants were found to be within the low risk range after the training session. All participants (n = 17) were able to increase their knee flexion angle from 88.8° at the baseline to 105° at the final evaluation session (MD 16.2; 95% CI 11.38 to 21.02).

The improvement of 16.2° in knee flexion in the study by Dowling., *et al.* [7]. is comparable to a previously reported value of 11.3° [29]. In the study by Miznar., *et al.* [29]. female athletes were able to increase the knee flexion angle in drop jump from 86.4° at the baseline test to 97.7° at the evaluation session. Participants practiced for five- minute after receiving brief verbal landing instructions, and knee flexion angles were measured using a seven cameras motion analysis system. Therefore, this identifies a limitation in Dowling., *et al.* [7] which is providing modification instructions to participants. Thus, it is difficult to infer whether knee angle improvements are solely owing to the feedback from the IMUs, or stem from the combined effects of feedbackfrom the IMUs and the set of movement modification. In both studies, the effect of both type of feedbacks (verbal and visual) were tested immediately after the training sessions [7,29]. Therefore, carry-over effects or retention of corrected knee angle and thereduction in risk of ACL injuries in long-term remains uncertain.

Limitations of the Study

The review being a narrative one, a risk of bias or quality assessment of the includedarticles was not done. Studies that focused on technical and calibration aspects of theIMUs were excluded, which might contain important information. Although quality assessments of the included studies were not performed in this review, there were clear methodological limitations in some of the included articles which could have influenced the findings of this review. For example, the majority of the validity studies involved healthy participants with small sample size and used different methodologies. Additionally, some studies did not sufficiently report the utilized statistical analyses. Only one study with methodological issues was identified in eachof the reliability and feedback categories, therefore, drawing conclusions would be difficult for these two sections. In the outcome and feedback sections, some of the included studies were compared with previously published studies and there were methodological differences between the compared studies.

Clinical Implications

For clinical measurements to be used in clinical situations, their reliability and validity must be determined as prerequisites.[30] Based on the findings of this narrativereview, it cannot yet be recommended that IMUs are used in clinical situations with individuals after knee injuries and/or surgeries. This is because that IMU reliability and IMU validity on knee symptomatic populations have not been established yet.

Future Research

The majority of the studies included in this review were conducted on asymptomaticpopulation. Thus, it would be beneficial to assess the validity and reliability of IMUsmeasurements on symptomatic knee populations in future researches. For outcome- based studies, it is valuable to choose knee kinematics variables that are known to bealtered after knee injuries and/or surgeries to compare between experimental and healthy groups. It is also imperative to know the effect of feedback provided only byIMUs and to determine the long-term effect of this feedback.

Conclusion

The findings of this narrative review show that IMU is valid to measure knee kinematics with acceptable errors in healthy participants during over-ground and treadmill walking. It is also valid to measure sagittal and transverse planes movements during stairs negotiation, however, IMU seems invalid for coronal plane movements in asymptomatic participants. Despite the presence of one study showed an excellent reliability of IMU for knee valgus and rotation during single leg squattingand landing, it is still inadequate to indicate the reliability of IMU to measure knee kinematics in both healthy and symptomatic populations. Additionally, IMU appears inappropriate to be utilized as an outcome measure for knee injuries and/or surgeries. It is difficult to draw a conclusion for IMUs application as a feedback tool as it is need further investigations.

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