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Application of motion capture technology for sport performance analysis
El uso de la tecnología de captura de movimiento para el análisis del rendimiento deportivo

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Abstract: In sport performance, motion capture aims at tracking and recording athletes' human motion in real time to analyze physical condition, athletic performance, technical expertise and injury mechanism, prevention and rehabilitation. The aim of this paper is to systematically review the latest developments of motion capture systems for the analysis of sport performance. To that end, selected keywords were searched on studies published in the last four years in the electronic databases ISI Web of Knowledge, Scopus, PubMed and SPORTDiscus, which resulted in 892 potential records. After duplicate removal and screening of the remaining records, 81 journal papers were retained for inclusion in this review, distributed as 53 records for optical systems, 15 records for non-optical systems and 13 records for markerless systems. Resultant records were screened to distribute them according to the following analysis categories: biomechanical motion analysis, validation of new systems and performance enhancement. Although optical systems are regarded as golden standard with accurate results, the cost of equipment and time needed to capture and postprocess data have led researchers to test other technologies. First, non-optical systems rely on attaching sensors to body parts to send their spatial information to computer wirelessly by means of different technologies, such as electromagnetic and inertial (accelerometry). Finally, markerless systems are adequate for free, unobstructive motion analysis since no attachment is carried by athletes. However, more sensors and sophisticated signal processing must be used to increase the expected level of accuracy.
Keywords: Inertial, Markerless, Accelerometry, Technology, Video.

Resumen: En el ámbito del rendimiento deportivo, el objetivo de la captura de movimiento es seguir y registrar el movimiento humano de deportistas para analizar su condición física, rendimiento, técnica y el origen, prevención y rehabilitación de lesiones. En este artículo, se realiza una revisión sistemática de los últimos avances en sistemas de captura de movimiento para el análisis del rendimiento deportivo. Para ello, se buscaron palabras clave en estudios publicados en los últimos cuatro años en las bases de datos electrónicas ISI Web of Knowledge, Scopus, PubMed y SPORTDiscus, dando lugar a 892 registros. Tras borrar duplicados y análisis del resto, se seleccionaron 81 artículos de revista, distribuidos en 53 registros para sistemas ópticos, 15 para sistemas no ópticos y 13 para sistemas sin marcadores. Los registros se clasificaron según las categorías: análisis biomecánico, validación de nuevos sistemas y mejora del rendimiento. Aunque los sistemas ópticos son los sistemas de referencia por su precisión, el coste del equipamiento y el tiempo invertido en la captura y postprocesado ha llevado a los investigadores a probar otras tecnologías. En primer lugar, los sistemas no ópticos se basan en adherir sensores a zonas corporales para mandar su información espacial a un ordenador mediante distintas tecnologías, tales como electromagnética y inercial (acelerometría). Finalmente, los sistemas sin marcadores permiten un análisis del movimiento sin restricciones ya que los deportistas no llevan adherido ningún elemento. Sin embargo, se necesitan más sensores y un procesado de señal avanzado para aumentar el nivel de precisión necesario.
Palabras clave: Inercial, Sin marcadores, Acelerometría, Tecnología, Vídeo.

Introduction

Performance analysis of sport aims at evaluating athletes' improvements as a consequence of training over an extended period of time, the degree of physical condition or technical expertise. Coaches looking for optimal performance and technique develop a tailored training plan and monitor outcomes by means of different tools (Southgate, Prinold, & Weinert-Aplin, 2016).

Analysis of human motion can be regarded as one of the most precise technique to address elite sports' outcomes. Topics as competitive performance, for example, achieving greater joint extension and acceleration to boost jump height (Chiu, Bryanton, & Moolyk, 2014), technique evaluation, such as changes in hip flexion-abduction to enhance technique in bars (Huchez, Haering, & Holvoët, 2013), prevention of injuries, for example by stating than females are more prone to knee injuries during the fencing lunge (Jonathan Sinclair & Bottoms, 2013), equipment optimization, for example, optimal bat weighting (Laughlin, Fleisig, Aune, & Diffendaffer, 2016), or team interaction, for example, in rowing (Ruffaldi, Peppoloni, & Filippeschi, 2015). All these systems aims at tracking the motion of body segments with which to compute appropriate joint and segment kinematics. Additional information can also be extracted with further processing, either from the device itself or by means of complex muscular and/or skeleton models.

There are two main methods of analyzing human movement for sport motion. On the one hand, in the video-based approach, cameras are used to record athletes during training or competition and provide them with extrinsic visual feedback (Pueo, 2016). This feedback can be delivered as soon the task is completed or after manual digitizing of the body landmarks of interest by mean of dedicated software. On the other hand, automatic tracking motion analysis systems, also known as motion capture, aims at tracking and recording human motion in real time without a delayed digitizing process (López, López, López, & Alonso, 2017). These systems use a variety of capturing techniques, from multiple video cameras working with infrared light to single-camera systems with additional sensors to retrieve depth information from scene (Liebermann et al., 2002).

Motion capture has widely been used for quantitative purposes in several sport disciplines and activities, such as technique and competition evaluation (Marqués, Cela, & Gisbert, 2017). Also, from a biomechanical perspective, motion capture is the primary source of data that helps researchers to gain knowledge of the mechanics governing human movement. More recently, optical motion capture has been compared to newer technologies based on optical, acoustical, electromagnetic and inertial sensor, allowing athletes to perform movements with minimal disturbance elements or eve without the need of any type of markers.

The aim of this paper is to systematically review the latest developments of motion capture systems for the analysis of sport performance. This review will focus on optical, non-optical and markerless systems under three distinctive categories: biomechanical motion analysis, validation of new systems and performance enhancement.

Methods

In order to identify recent relevant articles about motion capture, a systematic review of the available literature was conducted in the electronic databases ISI Web of Knowledge, Scopus, PubMed and SPORTDiscus over a four year period (1st January, 2013 – 31st December, 2016), using the following search string: («motion capture» OR «motion analysis» OR camera OR video OR inertial OR IMU OR markerless OR Kinect) AND (performance OR analysis). Selected articles included relevant results regarding the application of motion capture as a tool for sport performance analysis and had sufficient technical specifications of equipment and methodology used. Conference proceedings and studies failing to fall within the three above categories were excluded.

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Table 1:
Optical systems

	Authors, year	System, cameras, fps	Sample	Activity	Main results
a	(Arshi, Nabavi, Mehdizadeh, & Davids, 2015)	Vicon, 6, 200 Hz	18	Soccer	Power law could be implemented in an agility drill thus opening the way for establishment of a more representative measure of agility performance instead of drill duration.
a	(Bisesti et al., 2015)	Qualisys, 8, 240 Hz	15: 8m, 7f	Running	Running barefoot alters foot strike patterns and decreases knee extension joint moments. Cutting barefoot exposes the anterior cruciate ligament to strain no more than when shod, and may decrease undesirable mechanics related to anterior cruciate ligament injury.
a	(Cockcroft & Van Den Heever, 2016)	Vicon, 8, 200 Hz	15	Rugby	Even though the participants had variability in their run-up to the tee, final foot position next to the tee was very similar and consistent.
a	(Crotin & Ramsey, 2015)	Vicon, 8, 240 Hz	19	Baseball	Tracking ball velocity throughout a game provides instantaneous feedback to the pitcher, information that is required to maintain ball velocity irrespective of pitch accumulation.
a	(Crotin et al., 2014)	Vicon, 8, 240 Hz	19	Baseball	Stride length can affect physical exertion without disrupting ball velocity, where shortening strides can plausibly respond to competitive exertion in baseball pitchers.
a	(Danielsen, Sandbakk, Holmberg, & Ettema, 2015)	Qualisys, 7, 100 Hz	9m	Cross-country sky	Double poling involves a unique movement pattern different from most other forms of legged terrestrial locomotion, characterized primarily by inverted pendulum or spring-mass type.
a	(Greenhalgh & Sinclair, 2014)	Qualisys, 8, 250 Hz	30: 15m, 15f	Running	Male recreational runners may be at greater risk of Achilles tendon pathology.
a	(Hamill et al., 2014)	Qualisys, 8, 240 Hz	40	Running	Runners can alter their footfall pattern so there is a possible difference in the types of injuries that may be sustained between the forefoot and the rearfoot footfall patterns.
a	(Hansen C, Rezzoug N, Gorce P, 2015)	Vicon, 8, 250 Hz	10m	Baseball	The sequence-dependent rotation axes changes associated with the use of interaction torque during the acceleration phase could be a key factor in the production of hand velocity at ball release.
a	(Hejrati, Chesebrough, Bo Foreman, Abbott, & Merryweather, 2016)	Optitrack, 10, 120 Hz	13	Walking	Walking speed, surface slope, and individuals' height were the most important factors influencing arm swing during walking.
a	(Iino & Kojima, 2016)	Vicon, 8, 250 Hz	8m	Table tennis	Racket mass and speed highlights one of the advantages of playing close to the table and making the rally speed fast.
a	(Inoue et al., 2014)	Vicon, 10, 500 Hz	12m	Soccer	The interaction moment of the kicking was the main factor causing the pelvis counter- clockwise rotation within the horizontal plane from the overhead view that precedes a proximal-to-distal sequence of segmental action of the swing leg.
a	(Sinclair & Bottoms, 2013)	Qualisys, 8, 250 Hz	16: 8m, 8f	Fencing	Females produced greater knee abduction at the end of the lunge as well as greater hip adduction, so they could be at a greater risk of knee injuries due to the greater knee abduction and hip adduction produced during the fencing lunge.
a	(Joyce et al., 2013)	Vicon, 10, 250 Hz	15	Golf	Three of the six variables used to explain the variance in clubhead speed were from the lower trunk, which shows, in part, the importance of including segments such as the lower trunk when examining the golf swing.
a	(Lädermann et al., 2016)	Vicon, 24, 240 Hz	10	Tennis	Tennis players presented frequent radiographic signs of structural lesions that could mainly be related to posterosuperior impingements due to repetitive abnormal motion contacts.
a	(Martin et al., 2014)	Vicon, 12, 300 Hz	19	Tennis	Improper energy flow during the tennis serve can decrease ball velocity, increase upper limb joint kinetics, and thus increase overuse injuries of the upper limb joints.
a	(Martin, Kulpa, Delamarche, et al., 2013)	Vicon, 12, 300 Hz	10	Tennis	Sequence is crucial for ball velocity so improper temporal mechanics during the tennis serve can decrease ball velocity, increase upper limb joint kinetics, and thus possibly increase overuse injuries of the upper limb.
a	(Martin, Kulpa, Ropars, et al., 2013)	Vicon, 12, 300 Hz	20	Tennis	The timings of peak angular velocities of pelvis, upper torso, trunk rotations and the duration between instants of shoulder were significantly related to upper limb joint kinetics and ball velocity.
a	(Mehdizadeh, Arshi, & Davids, 2014)	Vicon, 5, 100 Hz	15m	Running	Stability is regulated when constraints on the speed of movements is altered, so slow running is more stable than fast running.
a	(Skublewska-Paszkowska et al., 2016)	Vicon, 8, 100 Hz	3m	Rowing	Developlement of an interdisciplinary research of rowers with a motion acquisition system, an EMG system, an ergometer and a heart rate monitor.
a	(Y. Zhang, Ma, & Liu, 2016)	Vicon, 8, 250 Hz [Optitrack, 10, 250 Hz]	8m	Bowling	No significant difference found between two types of cricket bowling techniques in trunk moments and lumbar spine force, thus the max-trunk technique may not increase lower back injury risks.
b	(Carse, Meadows, Bowers, & Rowe, 2013)	Optitrack, 8, 100 Hz [Vicon, 12, 100 Hz] [Vicon, 8, 120 Hz]	1	Gait	The Optitrack system provides a low-cost 3D motion analysis system that can offer marker tracking accuracy and reliability which is comparable with an older and still widely used system.
b	(Frayne, Dean, & Jenkyn, 2014)	M. Analysis, 10, 200 Hz	4	Ice Hockey	Linear and angular velocities of the puck, accuracy and puck topple were not different between bare hockey stick/normal hockey gloves and the remaining three grip conditions.
b	(Bernardina et al., 2016)	GoPro, 2, 60 Hz	2 SCF	Swimming	Action cameras can be made an accurate metric system by means of an opportune calibration methodology (handy tools and bundle adjustment).
b	(Hansen et al., 2014)	Vicon, 8, uns	3 SCF	Laboratory	The NaturalPoint OptiTrack 250e camera system is a reliable working system that can certainly be used in biomechanics and other related fields.
b	(Mundy, Lake, Carden, Smith, & Lauder, 2016)	Vicon, 10, 250 Hz	40m	Jumping	If power output is to be meaningfully investigated, a standardised method must be adopted since the force platform method and the combined method cannot be used interchangeably for measuring power output during the loaded CMJ.
b	(Pueo, Lipinska, Jiménez-Olmedo, Zmijewski, & Hopkins, 2016)	Optitrack, 8, 100 Hz [2 Jump-mat systems]	31m	Jumping	The jump-mat systems provide trustworthy measurements for monitoring changes in jump height. Foot length can explain the substantially higher jump height observed with motion capture.
b	(Thewlis, Bishop, Daniell, & Paul, 2013)	Optitrack, 12, 100 Hz [Vicon, 12, 100 Hz]	1 SCF	Laboratory	Low-cost motion capture systems are sufficiently accurate for general use; however, Vicon system outperformed the Natural Point system through vastly shorter marker labeling time.
c	(Betzler, Monk, Wallace, & Otto, 2014)	Qualisys, 5, 1000 Hz	285	Golf	Differences in clubhead presentation resulted in changes to ball launch conditions. Impact location variability plays a role in determining launch angle and total distance variability.
c	(Chiu et al., 2014)	Qualisys, 6, 120 Hz	16f	Jumping	Arm swing promotes use of a proximal-to-distal strategy, which is associated with greater net joint moments and segment accelerations, all together contributing to better vertical jump performance.
c	(Estevan et al., 2015)	Qualisys, 8, 240 Hz	10	Taekwondo	During the roundhouse kick in taekwondo inter-segment motion seems to be based on a proximo-distal pattern.
c	(Estevan et al., 2016)	Qualisys, 8, 247 Hz	8	Taekwondo	Including exercises that require in-phase movement could not only help athletes to acquire coordination stability but also efficiency.
c	(Estevan et al., 2013)	Qualisys, 8, 247 Hz	9	Taekwondo	Athletes should not adopt the 90° stance position because it will not enable them to achieve the best performance in the roundhouse kick.
c	(Gomo & van den Tillaar, 2015)	Qualisys, 6, 500Hz	12m	Powerlifting	Due to the differences in moment arm of the barbell about the elbow joint in the sticking region, there still might be a poor mechanical region for total force production that is joint angle-specific.
c	(Goss et al., 2015)	Vicon, 8, 240 Hz	89	Running	Runners often cannot report their foot-strike patterns accurately and may not automatically adopt an anterior–foot-strike pattern after transitioning to minimalist running shoes.
c	(Hart, Cochrane, Spiteri, Nimphius, & Newton, 2016)	Vicon, 10, 250 Hz	31	Australian Football	Resistance training and skill acquisition programs may play a role on the development of kicking accuracy since relative lean mass was positively correlated with kicking accuracy.
c	(Huchez, Haering, & Holvoët, 2013)	Vicon, 10, 250 Hz	8f	Gymnastics	The study provided directions for training: to increase hip flexion–abduction, to transfer leg and arm angular momentum to the trunk and to straighten hand path to the bar.
c	(Sinclair, Currigan, et al., 2014)	Qualisys, 8, 500 Hz	50	Golf	Sagittal plane wrist velocity and peak transverse plane torso rotation are the strongest contributors to ball velocity and potentially overall driving performance.
c	(Sinclair, Fewtrell, Taylor, Atkins, et al., 2014)	Qualisys, 10, 500 Hz	17m	Soccer	Additional bilateral training be undertaken in order to attenuate this and improve overall kicking performance since significantly higher ball, foot and knee extension velocities at ball contact were obtained with the dominant limb.
c	(Sinclair, Fewtrell, Taylor, Bottoms, et al., 2014)	Qualisys, 10, 500 Hz	22m	Soccer	Players may benefit from coaching towards the improvement of knee extension angular velocity as being the strongest contributor to ball velocity and potentially overall kicking performance.
c	(Laughlin, Fleisig, Aune, & Diffendaffer, 2016)	M. Analysis, 8, 500 Hz	40	Baseball	The ability to maintain swing kinematics with a handle-weighted bat may have implications for swing training and warm-up.
c	(Lazzeri, Kayser, & Armand, 2016)	Vicon, 12, 200 Hz	10	Unihockey	Ball speed was mainly influenced by the flexion of the supporting leg (ankle, knee and hip), by the rotation of the hip and of the trunk, and by the rotation and abduction– adduction movements of the wrist of the hand on the top of the stick.
c	(Lockie, Callaghan, & Jeffriess, 2014)	Vicon, 6, 200 Hz	18m	Kricket	Due to relationships with shoulder and leg motion, and the importance and trainability of step length, cricketers should target this variable to enhance acceleration to retrieve the ball.
c	(Lopes, Jacobs, Travieso, & Araújo, 2014)	Qualisys, 4, 150 Hz	12m	Soccer	Compound variables are often more useful than individual kinematic variables and are almost equally useful in deceptive and non-deceptive conditions.
c	(Martin, Bideau, Delamarche, & Kulpa, 2016)	Vicon, 12, 200 Hz	8	Tennis	The consistency in timing of maximal angular velocities suggests that advanced tennis players are able to maintain the temporal pattern of their serve technique, despite of the muscular fatigue.
c	(Maurer et al., 2015)	Vicon, 8, 200 Hz	20	Running	The influence of the lower jaw position on the running pattern revealed that the splint conditions lead to a more symmetrical running pattern than the control condition.
c	(Milanese, Corte, Salvetti, Cavedon, & Agostini, 2016)	Vicon, 8, 500 Hz	34m	Golf	Method of amplification of error is an effective strategy for correcting the technical errors leading to a rapid improvement in golf performance.
c	(Nedergaard, Heinen, Sloth, Holmberg, & Kersting, 2015)	Qualisys, 8, 236 Hz	7	Ski cross	The patterns of force and movement during indoor and outdoor starts were similar, demonstrating that indoor training ramps are suitable for training and monitoring elite teams during off-season.
c	(Otsuka, Ito, Honjo, & Isaka, 2016)	M. Analysis, 16, 250 Hz	10m	Running	Scapular behavior in first accelerated running contributes to larger upper- and lower-limb motions and facilitates coordinating whole-body balance for a fast sprint.
c	(Reid, Giblin, & Whiteside, 2014)	Vicon, 22, 250 Hz	28f	Tennis	Practitioners should be aware that the throw appears less useful for priming the specific arm kinematics and temporal phasing that typifies the tennis serve.
c	(Sommer, Häger, & Rönnqvist, 2014)	Qualisys, 8, 250 Hz	13m	Golf	General influences of synchronized metronome training on the underlying brain-based motor control strategies lead to a more coordinated movement pattern of the golf-swing performance.
c	(Z. Zhang et al., 2016)	Vicon, 10, 200 Hz	24	Badminton	Trunk rotation was shown to be vital for maximizing the release speed of the shuttlecock – an important measure of the quality of the forehand smash that skilled players master.
c	(Zago et al., 2015)	BTS, 9, 60 Hz	10m	Soccer	Faster players are able to run with the ball through a shorter path in a more economical way so coaches are encouraged to design specific practices where high stride frequency and narrow run trajectories are required.

First column. a: Motion Analysis, b: System validation, c: Performance enhancement.
Third column. System manufacturer, number of cameras, frames per second. Criterion reference system between brackets where available.
Fourth column. m: Male, f: Female, SCP: Standard Calibration Frame.

Table 2:
Non-optical systems

	Authors, year	System, sensors, freq.	Sample	Activity	Main results
a	(Gageler et al., 2013)	IMU, 1, 100 Hz [100g accel., 100 Hz]	3	Running	Frequent and rapid stops may result in earlier onset of muscle and joint fatigue as well increasing the possibility of injury.
a	(Norcross et al., 2013a, 2013b)	EM, 120 Hz	82: 41m, 41f	Jumping	Greater sagittal-plane initial impact phase energy absorption likely indicates greater anterior cruciate ligament loading, whereas in the frontal-plane, it was associated with less favorable frontal-plane biomechanics.
b	(Bötzel, Marti, Rodríguez, Plate, & Vicente, 2016)	IMU, 2 (one on each shank) [Qualisys, 8, 200 Hz]	14m	Gait	This new gait recording systems aims to assess the temporal and spatial descriptors, such as that heel-off moment was reliably at 51% of the step cycle, irrespective of gait velocity.
b	(Fasel, Favre, Chardonnens, Gremion, & Aminian, 2015)	IMU, 2, 500 Hz (ski and pole)	10: 4m, 6f	Cross-country sky	This study introduced an easy-to-use system to measure the spatio-temporal parameters in diagonal stride XC skiing by integrating the IMUs in the poles and skis.
b	(Fasel, Praz, Kayser, & Aminian, 2016)	IMU, 1 (left ski) [Vicon, 7, 200 Hz]	12	Ski mountaineer	The adapted algorithm proved valid for measuring spatio-temporal parameters for ski-mountaineering on treadmill and is expected to perform similarly on snow.
b	(McGinnis et al., 2016)	IMU, 2, 300 Hz [Vicon, 100 Hz]	16	Jumping	Changes in kinematic parameters were evident across conditions, and several changes were significantly associated with changes in jump performance.
b	(Rantalainen, Hart, Nimphius, & Wundersitz, 2016)	IMU, 1, 100 Hz [M.Analysis, 12, 200 Hz]	39	Gait	Resultant and vertical acceleration derived results had excellent agreement, which suggests that acceleration is a viable alternative to considering the acceleration dimensions independently.
b	(Telfer et al., 2014)	US, Probe [Qualisys, 8, 120 Hz]	14	Gait	Ultrasound and motion capture is a non-invasive technique which may help to provide more accurate measurements of intrinsic foot kinematics.
b	(Wang et al., 2014)	Radar [Vicon, 100 Hz]	13: 7f, 6m	Gait	The capability of the system to be used as a daily gait assessment tool in home environments, useful for fall risk assessment and other health care applications.
b	(Papi, Osei-Kuffour, Chen, & McGregor, 2015)	IMU, 2 [Vicon, 10, 100 Hz]	14: 7f, 7m	Walking	The potential use of wearable technologies, located in functional placements, is valid for assessing subject performance during exercise and suggests functional solutions to enhance acceptance.
b	(Ruffaldi et al., 2015)	IMU, 5, 100 Hz (back, upper & fore arm) [Vicon, 7, 100 Hz]	1	Rowing	A novel approach to track out-door rowing performance based on the fusion of data gathered from the instrumented boat or simulator and body motion data obtained from inertial sensors.
b	(Zorko et al., 2015)	IMU, 1, 120 Hz [RTK GNSS]	6	Alpine ski	Skis with large waist widths on hard, frozen surfaces could bring the knee joint unfavorably closer to the end of the ROM in transversal and frontal planes, thus increasing the risk of knee injuries.
c	(Kasmer et al., 2014)	EM, 60 Hz	4	Running	After the 50-km run in the traditional shoe type and in the minimalist shoe type, there may be a change in motor unit recruitment pattern during long-distance, sustained velocity running.
c	(Y.-K. Kim, 2013)	EM, 12, 240 Hz	20m	Baseball	In overloaded warm-up, baseball players should have at least more than 3 dry swings with a 3-min rest to maximize the effect of post-activation potentiation and to minimize the effect fatigue.
a	(Gageler et al., 2013)	IMU, 1, 100 Hz [100g accel., 100 Hz]	3	Running	Frequent and rapid stops may result in earlier onset of muscle and joint fatigue as well increasing the possibility of injury.

First column. a: Motion Analysis, b: System validation, c: Performance enhancement.
Third column. System manufacturer, number of sensors, adquisition frequency. IMU: Inertial Measurement Unit, EM: Electromagnetic, US: Ultrasonics, RTK GNSS: Real Time Kinematic Global Navigation Satellite Systems. Criterion reference system between brackets where available.
Fourth column. m: Male, f: Female, SCP: Standard Calibration Frame

Results

An initial search identified 892 records. After duplicate removal and screening of the remaining records, 81 full-text papers were retained for inclusion in this review, distributed as 53 records for optical systems (Table 1), 15 records for non-optical systems (Table 2) and 13 records for markerless systems (Table 3). Resultant records were screened to distribute them according to the following analysis categories: (a) biomechanical motion analysis, (b) validation of new systems and (c) performance enhancement.

Optical systems

These systems track either passive (reflective spheres) or active (LEDs) markers placed on body landmarks to triangulate their 3D position. Generally, eight or more cameras are necessary for full-body capture through different marker sets comprising around 40 markers at specific anatomic landmarks (Cappozzo, Catani, Della Croce, & Leardini, 1995). Actual systems can capture from 100 frames per second (fps) to 500 fps, although higher frame rates can be achieved by decreasing image resolution. Alternatively, fps number is also displayed as image capture frequency in hertz (Hz), where 1 fps equals 1 Hz.

Optical motion capture has been used in sports with implements for assessing ball velocity, as a function of several biomechanical conditions, such as stride length (Crotin, Kozlowski, Horvath, & Ramsey, 2014) or sequence-dependent rotation axes (Hansen C, Rezzoug N, Gorce P, 2015) in baseball, lower trunk (Joyce, Burnett, Cochrane, & Ball, 2013) and torso rotation (Sinclair, Currigan, Fewtrell, & Taylor, 2014) in golf and upper limb joint (Martin et al., 2014; Martin, Kulpa, Delamarche, & Bideau, 2013; Martin, Kulpa, Ropars, Delamarche, & Bideau, 2013). In running, studies focus mainly on foot strike patterns

Table 3:
Markerless systems

	Authors, year	System, sensors, freq.	Sample	Activity	Main results
a	(Abrams et al., 2014)	Video, 8, 200 Hz	7m	Tennis	The kick serve had a higher force magnitude at the back than the flat and slice as well as larger posteriorly directed shoulder forces, whereas the flat serve had significantly greater maximum shoulder internal rotation velocity versus the slice serve.
b	(Auvinet, Multon, & Meunier, 2015)	Kinect, 30 Hz [Vicon, 12, 120 Hz]	NA	Gait	The correlation coefficient between gait index measured by Kinect and by motion capture is 0.968, so Kinect is a low cost, promising development procedure for clinical gait analysis.
b	(Eltoukhy et al., 2016)	Kinect, 30 Hz [BTS, 8, 250 Hz]	10; 5m, 5f	Jumping	Kinetic may not be an appropriate surrogate for traditional motion analysis technology, but it may have potential applications as a real-time feedback tool in pathological/ high injury risk populations.
b	(O'Keefe et al., 2014)	Video, 14 [Hyperactivity scales]	20m	Laboratory	Results suggest feasibility and validity of a markerless system as a non-invasive method able to quantify motion in individuals with hyperkinesis.
b	(Pfister, West, Bronner, & Noah, 2014)	Kinect, 30 Hz (Brekel) [Vicon, 10, 120 Hz]	20	Gait	The Kinect has basic motion capture capabilities to be a proper tool to measure stride timing, but more advances are necessary to improve its sensitivity before it can be implemented for clinical use.
b	(Sandau et al., 2014)	Video, 8, 75 Hz	10	Gait	Flexion/extension angles as well as hip abduction/adduction closely resembled those obtained from the marker based system. However, the internal/external rotations, knee abduction/adduction and ankle inversion/eversion were less reliable.
b	(Schmitz et al., 2015)	Kinect, 30 Hz (SDK 1.8) [M.Analysis, 10, 200 Hz]	NA	Laboratory	The Kinect agreed well with the marker-based system in terms of the pattern of the motion, the reliability, and peak angles calculated, so it may be a feasible markerless motion capture tool that can be used in the clinic.
b	(Bonnechère et al., 2014)	Kinect, 30 Hz (SDK 1.5) [Vicon, 8, 60 Hz]	48	Laboratory	Kinect reproducibility was found to be statistically similar to marker-based system results for the four exercises. However, measured ROM however were found different between the systems.
b	(Clark, Bower, Mentiplay, Paterson, & Pua, 2013)	Kinect, 30 Hz (SDK 1.0) [Vicon, 12, 120 Hz]	21	Gait	The Kinetic could provide clinicians with significant advantages for assessing some spatiotemporal gait parameters. However, some commonly reported variables cannot be accurately measured.
b	(J. Kim et al., 2015)	Xtion, 30 Hz [Vicon, 120 Hz]	10; 5m, 5f	Walking	The proposed treadmill achieves similar performance to a typical, costly, interactive treadmill that contains a motion capture system and an instrumented treadmill.
b	(Krigslund et al., 2013)	RFID tags (thigh and shank) [Qualisys, 8, 100 Hz]	1	Walking	Although the method is in its initial phase of development, the results are promising and show that the movement information can be extracted from the RFID response signals.
b	(Schmitz, Ye, Shapiro, Yang, & Noehren, 2014)	Kinect, 30 Hz (KinectFusion) [M. Analysis, 10 200 Hz]	Testing jig	Laboratory	The Kinetic is effective to accurately measure lower extremity kinematics and provide a first step to discern clinically relevant differences in the joint kinematics of patient populations.
b	(Yeung, Cheng, Fong, Lee, & Tong, 2014)	Kinect, 30 Hz (SDK b2) [Vicon, 80, 240 Hz]	10m	Stability	Kinect system produced highly correlated measurement of total body center of mass sway, so it is a cost-effective alternative to a motion capture and force plate system for clinical assessment of sway.

First column. a: Motion Analysis, b: System validation, c: Performance enhancement.
Third column. System manufacturer, number of sensors, adquisition frequency (software). SDK: Software Development Kit. Criterion reference system between brackets where available.
Fourth column. m: Male, f: Female, SCP: Standard Calibration Frame

(Bisesti, Lawrence, Koch, & Carlson, 2015; Goss et al., 2015; Hamill, Gruber, & Derrick, 2014). Kicking biomechanics to increase efficiency is the primary target in soccer (Inoue, Nunome, Sterzing, Shinkai, & Ikegami, 2014; Sinclair, Fewtrell, Taylor, Bottoms, et al., 2014; Sinclair, Currigan, et al., 2014; Zago et al., 2015). Sports with emphasis on technical executions also benefit from optical motion capture, such as taekwondo (Estevan, Falco, Silvernail, & Jandacka, 2015; Estevan, Freedman Silvernail, Jandacka, & Falco, 2016; Estevan, Jandacka, & Falco, 2013).

Optical motion capture is a time-consuming system that requires long preparation at the laboratory (each athlete must wear a full body capture suit with marker sets) and postprocessing to clean all corrupted data, such as occlusions or marker swaps. Therefore, the sample is rather low, being 20 a mean value across records. In validation studies, where absolute differences from various methods may arise under same circumstances, standard calibration frames are also used. These tools consist of geometrical structures carrying two or more markers at known distances, generally used for system calibration.

Regarding optical systems' manufacturers, there is a preference for two systems: Vicon, Oxford Metrics, UK (26 records) and Qualysis AB, Sweden (17 records), with the 9 remainder records distributed between 3 manufacturers. The number of cameras ranges between 24 for a structural lesions study in tennis players (Lädermann, Chagué, Kolo, & Charbonnier, 2016) and only two for an underwater motion capture proposal made with action cameras (Bernardina, Cerveri, Barros, Marins, & Silvatti, 2016) by means of Direct Linear Transformation (DLT), first introduced by Abdel-Aziz & Karara (1971). Finally, except for two outliers, image capture frequency goes from 100 Hz to 500 Hz, depending on the system. From these figures, a typical optical system would consist of 12 cameras working at 200 Hz from the two major manufacturers. Such an experimental setup would fulfill a number of sport analyses.

Non-optical systems

Unlike the above technology, non-optical systems use sensors attached to body parts to send data about their position in space. Electromagnetic systems are composed of small electric coils (three per sensor, orthogonally) within a well-defined electromagnetic field created by a powerful source. Athlete's movements are tracked when coils generate small voltage or current inside a constant magnetic flux. As demonstrated in the four records with EM tag in Table 2, each sensor is able to read location and orientation simultaneously, but any metal object in the vicinity of sensors may introduce distortions in the magnetic field, ruining measurement accuracy. For example, in (Y.-K. Kim, 2013), the weighting supplement on arms and bats (Valeo, USA), as well as the bat itself, is non-metal to avoid interferences with the 4'' by 4'' global reference frame transmitter. Only two manufacturers are used in these records: on the one hand, Polhemus, USA, in a single-sensor setup, ranging from 60 Hz (Kasmer, Ketchum, & Liu, 2014) to 120 Hz (Norcross et al., 2013a, 2013b) and on the other hand, Motion Star, USA, in a 12-sensor setup working at 240 frames per second.

Inertial system technology is another kind of non-optical systems based on inertial measurement units (IMU), which are small micromechanical sensors containing accelerometers (Leirós-Rodríguez, Arce, García-Soidán, & Naveira-Barbeito, 2017), usually tri-axial to measure the three coordinates, and often combined with gyroscopes and magnetometers. For static subjects, accelerometers are able to measure angular rotations, however, for dynamic motions, gyroscopes and magnetometers are combined with accelerometry through sensor fusion algorithms. Inertial system data is often transmitted wirelessly to a computer in real-time with 6 degrees of freedom per sensor.

Since IMUs can be regarded as an emerging technology, studies on sport science are devoted to well-known sport biomechanics, such as gait/walking (5 records) and running (2 records), out of 10 records. Generally, such systems are compared to optical systems as reference criterion or used in conjunction with them to complement data, with the characteristics described above. However, in (Zorko, Nemec, Babiè, Lešnik, & Supej, 2015), a Real Time Kinematic Global Navigation Satellite Systems (RTK GNSS) is used to merge inertial data with high-definition and high-frequency real-time geolocalization to track skis in alpine skiing. Similarly, Gageler, Thiel, Neville, & James (2013), used an IMU with a ±8g tri-axial accelerometer placed in the middle to upper thoracic vertebrae and an additional custom-build IMU containing a 100g accelerometer attached to the distal Fibulas to measure vertical accelerations in running, where ground impacts were expected to exceed the range of 8g provided by the first IMU. The number of IMUs in each study is very low to date, with one or two IMUs at specific locations. However, Ruffaldi, Peppoloni, & Filippeschi (2015) proposed a novel approach to track outdoor rowing performance from different instruments, including one IMU located on the trunk in the midpoint between the scapula, and two IMUs for each upper limb, on the arm and the forearm. This study shows that one of the IMUs potential is their suitability for indoor and outdoor experiments due to their low mass and minimum invasive behavior.

New non-optical technologies have also been tested in the sport science field. For example, Telfer, Woodburn, & Turner (2014) used an intraoperative 13 MHz linear array ultrasound probe (IOE 323, Italy) at 47 Hz to demonstrate that, together with an optical motion capture, intrinsic foot kinematics may be measured accurately. Similarly, Wang, Skubic, Rantz, & Cuddihy (2014) proposed to use a shelf pulse doppler range control radar (PrecisionLine, USA), originally designed as motion detectors in home security systems, to track the walk segment suitable for gait analysis as different human body parts generate different radar signatures.

Finally, there are other motion capture systems, like the mechanical motion (Menache, 2011), which consist of rigid structures attached to joints of the body that articulate as subject's body is in motion. Although being a low-cost and real-time via wireless system, such technology is not used in sport sciences since exoskeletons prevent athletes from performing unobstructed natural motions.

Markerless systems

Finally, sophisticated computer image processing is emerging to reconstruct 3D motion from video and other sensors without subjects needing to wear special equipment for tracking. Generally, commercial videogame and entertainment 3D cameras, comprising one or two regular video cameras, together with infrared and ultrasonic sensors, are used to identify human forms from which to extract body segments and joints.

As with non-optical systems, this relatively newly introduced technology has been used in studies with tested biomechanics, such as gait/walking (6 records) and laboratory tests in which controlled motions are assessed (4 records). The remaining 3 records cover different activities, such as jumping, stability or tennis. The fact that no marker is needed for capturing allows for the test of a number of subjects: excluding a study with one subject, the mean value is 17 subjects per experiment, with several studies comprising 48 and 20 subjects.

The Kinect camera is the technology mostly used in markerless systems (8 out of 9 records). As part of Xbox video console, it consists of a 30 Hz video camera, a depth sensor (infrared laser projector) and multi-array microphone. The original aim was to provide full body motion capture, facial and voice recognition for gaming, but these features have been used by sport scientists with third-party developments and custom-build software by means of software development kit (SDK), provided by Microsoft. Alternative depth cameras are found in (J. Kim, Gravunder, & Park, 2015), where a Asus Xtion was used with similar features as Kinect: video camera and depth sensor. The main disadvantage of both depth cameras is the level of spatial and temporal accuracy. Video cameras in such systems usually work at 640x480 pixels resolution, which would be enough for body recognition in gaming, but for applications where the aim is to track the motion of a body segment, some issues may appear. Across studies presented in this paper, conclusions pointed out that it is a promising technology, but more data processing is necessary, together with fusion with other sensors, such as additional video cameras, to reach a proper accuracy. Regarding temporal resolution, a fixed 30 fps capability may limit its use for slow to moderate velocity motions.

Another technique to retrieve information on body segments is the use of a number of video cameras and a later image processing (Abdel-Aziz & Karara, 1971). Abrams, Harris, Andriacchi, Safran, & Safran (2014) scanned seven tennis players with laser and then used eight cameras (resolution 640x480 pixels, 200 fps) to track tennis serves. Sandau et al. (2014) used eight cameras with higher resolution but lower framerate (2048x2048 pixels, 75 fps) to track gait motion. O'Keefe et al. (2014) tracked the travelled distance of the body center of mass, forearm, and foot and motion frequency of the latter of fragile X syndrome patients with fourteen cameras distributed in a canvas of 3.5 m x 4.9 m.

Finally, non-conventional methods have also been explored to validate them as alternative to optical and non-optical systems. Krigslund et al. (2013) proposed the use of Radio Frequency Identification (RFID) tags, generally used for object identification and gross localization, to track thigh and shank motions in the sagittal plane.

Conclusion

In this paper, a systematic review of the latest developments of motion capture systems for the analysis of sport performance has been addressed. Although restricted to journals in the last four years, the number of records has been very high, indicating the interest of this topic.

Optical systems have been tested in sport sciences and other disciplines for years, so they can be regarded as reference criterion in most studies with accurate results. However, being a time-consuming process and the cost of laboratory equipment makes it difficult for individuals and small organizations to use them.

In order to overcome these drawbacks, non-optical systems have emerged over the years. They all rely on attaching sensors to body parts to send their space coordinates and rotations in three perpendicular axes to computer wirelessly. Two major technologies are used to this end, electromagnetic and inertial (accelerometry) with accurate results. Less conventional methods have also been tested, such as ultrasonics and radar, but their suitability for sport sciences is rather questionable.

Finally, markerless systems are a step forward in motion capture, since no attachment is carried by subjects, allowing for a free, unobstructive motion. Kinect technology is the key technology used in these studies since it offers several advantages: low cost equipment, easy setup, both subject and researcher and real-time results. However, the level of accuracy expected for clinical and experimental research is still far from proper standards. By means of integrating more sensors and signal processing, accurate results may be obtained in a near future.

References

Abdel-Aziz, Y. ., & Karara, H. M. (1971). Direct Linear Transformation from Comparator Coordinates into Object Space Coordinates in Close-Range Photogrammetry. *American Society of Photogrammetry*, *81*(2), 1–18. https://doi.org/10.14358/PERS.81.2.103

Abrams, G. D., Harris, A. H., Andriacchi, T. P., Safran, M. R., & Safran, M. (2014). Biomechanical analysis of three tennis serve types using a markerless system. *Br J Sports Med*, *48*, 339–342. https://doi.org/10.1136/bjsports-2012-091371

Arshi, A. R., Nabavi, H., Mehdizadeh, S., & Davids, K. (2015). An alternative approach to describing agility in sports through establishment of a relationship between velocity and radius of curvature. *Journal of Sports Sciences*, *33*(13), 1349–55. https://doi.org/10.1080/02640414.2014.990481

Auvinet, E., Multon, F., & Meunier, J. (2015). New Lower-Limb gait asymmetry indices based on a depth camera. *Sensors*, *15*(3), 4605–4623. https://doi.org/10.3390/s150304605

Bernardina, G. R. D., Cerveri, P., Barros, R. M. L., Marins, J. C. B., & Silvatti, A. P. (2016). Action Sport Cameras as an Instrument to Perform a 3D Underwater Motion Analysis. *Plos One*, *11*(8). https://doi.org/10.1371/journal.pone.0160490

Betzler, N. F., Monk, S. a., Wallace, E. S., & Otto, S. R. (2014). The relationships between driver clubhead presentation characteristics, ball launch conditions and golf shot outcomes. *Journal of Sports Engineering and Technology*, *228*(4), 242–249. https://doi.org/10.1177/1754337114541884

Bisesti, B. A., Lawrence, M. A., Koch, A. J., & Carlson, L. A. (2015). Comparison of Knee Moments and Landing Patterns During a Lateral Cutting Maneuver: Shod Vs. Barefoot. *Journal of Strength and Conditioning Research*, *29*(11), 3075–3078. https://doi.org/10.1519/JSC.0000000000001134

Bonnechère, B., Jansen, B., Salvia, P., Bouzahouene, H., Omelina, L., Moiseev, F., … Van Sint Jan, S. (2014). Validity and reliability of the Kinect within functional assessment activities: Comparison with standard stereophotogrammetry. *Gait and Posture*, *39*(1), 593–598. https://doi.org/10.1016/j.gaitpost.2013.09.018

Bötzel, K., Marti, F. M., Rodríguez, M. Á. C., Plate, A., & Vicente, A. O. (2016). Gait recording with inertial sensors - How to determine initial and terminal contact. *Journal of Biomechanics*, *49*(3), 332–337. https://doi.org/10.1016/j.jbiomech.2015.12.035

Cappozzo, A., Catani, F., Della Croce, U., & Leardini, A. (1995). Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clinical Biomechanics*, *10*(4), 171–178. https://doi.org/10.1016/0268-0033(95)91394-T

Carse, B., Meadows, B., Bowers, R., & Rowe, P. (2013). Affordable clinical gait analysis: An assessment of the marker tracking accuracy of a new low-cost optical 3D motion analysis system. *Physiotherapy*, *99*(4), 347–351. https://doi.org/10.1016/j.physio.2013.03.001

Chiu, L. Z. F., Bryanton, M. A., & Moolyk, A. M. (2014). Proximal-to-distal sequencing in vertical jumping with and without arm swing. *Journal of Strength and Conditioning Research*, *28*(5), 1195–1202. https://doi.org/10.1519/JSC.0000000000000388

Clark, R. A., Bower, K. J., Mentiplay, B. F., Paterson, K., & Pua, Y. H. (2013). Concurrent validity of the Microsoft Kinect for assessment of spatiotemporal gait variables. *Journal of Biomechanics*, *46*(15), 2722–2725. https://doi.org/10.1016/j.jbiomech.2013.08.011

Cockcroft, J., & Van Den Heever, D. (2016). A descriptive study of step alignment and foot positioning relative to the tee by professional rugby union goal-kickers. *Journal of Sports Sciences*, *34*(4), 321–9. https://doi.org/10.1080/02640414.2015.1050599

Crotin, R. L., Kozlowski, K., Horvath, P., & Ramsey, D. K. (2014). Altered stride length in response to increasing exertion among baseball pitchers. *Medicine and Science in Sports and Exercise*, *46*(3), 565–571. https://doi.org/10.1249/MSS.0b013e3182a79cd9

Crotin, R. L., & Ramsey, D. K. (2015). Stride Length/ : A reactive response to prolonged exertion potentially effecting ball velocity among baseball pitchers. *International Journal of Performance Analysis in Sport*, *15*(1), 254–267.

Danielsen, J., Sandbakk, O., Holmberg, H. C., & Ettema, G. (2015). Mechanical Energy and Propulsion in Ergometer Double Poling by Cross-country Skiers. *Medicine and Science in Sports and Exercise*, *47*(12), 2586–2594. https://doi.org/10.1249/MSS.0000000000000723

Eltoukhy, M., Kelly, A., Kim, C.-Y., Jun, H.-P., Campbell, R., & Kuenze, C. (2016). Validation of the Microsoft Kinect® camera system for measurement of lower extremity jump landing and squatting kinematics. *Sports Biomechanics / International Society of Biomechanics in Sports*, *3141*(February), 1–14. https://doi.org/10.1080/14763141.2015.1123766

Estevan, I., Falco, C., Silvernail, J. F., & Jandacka, D. (2015). Comparison of Lower Limb Segments Kinematics in a Taekwondo Kick. An Approach to the Proximal to Distal Motion. *Journal of Human Kinetics*, *47*(1), 41–49. https://doi.org/10.1515/hukin-2015-0060

Estevan, I., Freedman Silvernail, J., Jandacka, D., & Falco, C. (2016). Segment coupling and coordination variability analyses of the roundhouse kick in taekwondo relative to the initial stance position. *Journal of Sports Sciences*, *34*(18), 1766–73. https://doi.org/10.1080/02640414.2015.1137342

Estevan, I., Jandacka, D., & Falco, C. (2013). Effect of stance position on kick performance in taekwondo. *Journal of Sports Sciences*, *31*(16), 1815–22. https://doi.org/10.1080/02640414.2013.803590

Fasel, B., Favre, J., Chardonnens, J., Gremion, G., & Aminian, K. (2015). An inertial sensor-based system for spatio-temporal analysis in classic cross-country skiing diagonal technique. *Journal of Biomechanics*, *48*(12), 3199–3205. https://doi.org/10.1016/j.jbiomech.2015.07.001

Fasel, B., Praz, C., Kayser, B., & Aminian, K. (2016). Measuring spatio-temporal parameters of uphill ski-mountaineering with ski-fixed inertial sensors. *Journal of Biomechanics*, 1–4. https://doi.org/10.1016/j.jbiomech.2016.06.017

Frayne, R. J., Dean, R. B., & Jenkyn, T. R. (2014). Improving ice hockey slap shot analysis using three-dimensional optical motion capture: A pilot study determining the effects of a novel grip tape on slap shot performance. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *229*(2), 136–144. https://doi.org/10.1177/1754337114562096

Gageler, W. H., Thiel, D., Neville, J., & James, D. A. (2013). Feasibility of using virtual and body worn inertial sensors to detect whole-body decelerations during stopping. *Procedia Engineering*, *60*(0), 28–33. https://doi.org/10.1016/j.proeng.2013.07.040

Gomo, O., & van den Tillaar, R. (2015). The effects of grip width on sticking region in bench press. *Journal of Sports Sciences*, (July), 1–7. https://doi.org/10.1080/02640414.2015.1046395

Goss, D. L., Lewek, M., Yu, B., Ware, W. B., Teyhen, D. S., & Gross, M. T. (2015). Lower extremity biomechanics and self-reported foot-strike patterns among runners in traditional and minimalist shoes. *Journal of Athletic Training*, *50*(6), 603–611. https://doi.org/10.4085/1062-6050.49.6.06

Greenhalgh, A., & Sinclair, J. (2014). Comparison of Achilles Tendon Loading Between Male and Female Recreational Runners. *Journal of Human Kinetics*, *44*(44), 155–159. https://doi.org/10.2478/hukin-2014-0121

Hamill, J., Gruber, A. H., & Derrick, T. R. (2014). Lower extremity joint stiffness characteristics during running with different footfall patterns. *European Journal of Sport Science*, *14*(2), 130–136. https://doi.org/10.1080/17461391.2012.728249

Hansen, C., Gibas, D., Honeine, J.-L., Rezzoug, N., Gorce, P., & Isableu, B. (2014). An inexpensive solution for motion analysis. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *228*(3), 165–170. https://doi.org/10.1177/1754337114526868

Hansen C, Rezzoug N, Gorce P, V. G. & I. B. (2015). Sequence-dependent rotation axis changes and interaction torque use in overarm throwing. *Journal of Sports Sciences*, 1–8. https://doi.org/10.1080/02640414.2015.1076167

Hart, N. H., Cochrane, J. L., Spiteri, T., Nimphius, S., & Newton, R. U. (2016). Relationship between leg mass, leg composition and foot velocity on kicking accuracy in Australian football. *Journal of Sports Science and Medicine*, *15*(2), 344–351.

Hejrati, B., Chesebrough, S., Bo Foreman, K., Abbott, J. J., & Merryweather, A. S. (2016). Comprehensive quantitative investigation of arm swing during walking at various speed and surface slope conditions. *Human Movement Science*, *49*, 104–115. https://doi.org/10.1016/j.humov.2016.06.001

Huchez, A., Haering, D., & Holvoët, P. (2013). Local versus global optimal sports techniques in a group of athletes. *Computer Methods in Biomechanics and Biomedical Engineering*, *18*(October), 37–41. https://doi.org/10.1080/10255842.2013.849341

Iino, Y., & Kojima, T. (2016). Mechanical energy generation and transfer in the racket arm during table tennis topspin backhands. *Sports Biomechanics*, *15*(2), 180–197. https://doi.org/10.1080/14763141.2016.1159722

Inoue, K., Nunome, H., Sterzing, T., Shinkai, H., & Ikegami, Y. (2014). Dynamics of the support leg in soccer instep kicking. *Journal of Sports Sciences*, *32*(11), 1023–32. https://doi.org/10.1080/02640414.2014.886126

Joyce, C., Burnett, A., Cochrane, J., & Ball, K. (2013). Three-dimensional trunk kinematics in golf: between-club differences and relationships to clubhead speed. *Sports Biomechanics*, *12*(2), 108–120. https://doi.org/10.1080/14763141.2012.728244

Kasmer, M. E., Ketchum, N. C., & Liu, X. C. (2014). The effect of shoe type on gait in forefoot strike runners during a 50-km run. *Journal of Sport and Health Science*, *3*(2), 122–130. https://doi.org/10.1016/j.jshs.2014.03.005

Kim, J., Gravunder, A., & Park, H.-S. (2015). Commercial Motion Sensor Based Low-Cost and Convenient Interactive Treadmill. *Sensors*, *15*(9), 23667–23683. https://doi.org/10.3390/s150923667

Kim, Y.-K. (2013). The Effect of Different Warm-up Procedures on Bat Speed in Baseball. *Korean Journal of Sport Biomechanics*, *23*(2), 91–97. https://doi.org/10.5103/KJSB.2013.23.2.091

Krigslund, R., Dosen, S., Popovski, P., Dideriksen, J. L., Pedersen, G. F., & Farina, D. (2013). A Novel Technology for Motion Capture Using Passive UHF RFID Tags. *Biomedical Engineering, IEEE Transactions on*, *60*(5), 1453–1457. https://doi.org/10.1109/TBME.2012.2209649

Lädermann, A., Chagué, S., Kolo, F. C., & Charbonnier, C. (2016). Kinematics of the shoulder joint in tennis players. *Journal of Science and Medicine in Sport*, *19*(1), 56–63. https://doi.org/10.1016/j.jsams.2014.11.009

Laughlin, W. A., Fleisig, G. S., Aune, K. T., & Diffendaffer, A. Z. (2016). 317. The effects of baseball bat mass properties on swing mechanics, ground reaction forces, and swing timing. *Sports Biomechanics*, *15*(1), 36–47. https://doi.org/10.1080/14763141.2015.1123762

Lazzeri, M., Kayser, B., & Armand, S. (2016). Kinematic predictors of wrist shot success in floorball/unihockey from two different feet positions. *Journal of Sports Sciences*, 1–8. https://doi.org/10.1080/02640414.2016.1151919

Leirós-Rodríguez, R., Arce, M. E., García-Soidán, J. L., & Naveira-Barbeito, G. (2017). Accelerometers/ : Devices that contribute to healthy aging. *Retos. Nuevas Tendencias En Educación Física, Deporte Y Recreación*, *32*, 44–47.

Liebermann, D., Katz, L., Hughes, M., Bartlett, R., McClements, J., & Franks, I. (2002). Advances in the Application of Information Technology to Sport Performance. *Journal of Sports Sciences*, *20*, 755–769. https://doi.org/10.1080/026404102320675611

Lockie, R. G., Callaghan, S. J., & Jeffriess, M. D. (2014). Acceleration kinematics in cricketers: Implications for performance in the field. *Journal of Sports Science and Medicine*, *13*(1), 128–136.

Lopes, J. E., Jacobs, D. M., Travieso, D., & Araújo, D. (2014). Predicting the lateral direction of deceptive and non-deceptive penalty kicks in football from the kinematics of the kicker. *Human Movement Science*, *36*, 199–216. https://doi.org/10.1016/j.humov.2014.04.004

López, J. L., López, D., López, A., & Alonso, C. (2017). Influence of footwear on foot movement during walking and running in boys and girls aged 6-7. *Retos. Nuevas Tendencias En Educación Física, Deporte Y Recreación*, *31*, 128–132.

Marqués, L., Cela, J., & Gisbert, M. (2017). Pre-service Physical Education Teachers ' self-management ability/ : a training experience in 3D simulation environments. *Retos. Nuevas Tendencias En Educación Física, Deporte Y Recreación*, *32*, 30–34.

Martin, C., Bideau, B., Bideau, N., Guillaume, N., Delamarche, P., & Kulpa, R. (2014). Energy Flow Analysis During the Tennis Serve Comparison Between Injured and Noninsured Tennis Players. *The American Journal of Sports Medicine*, *42*(22), 2751–2760. https://doi.org/10.1177/0363546514547173

Martin, C., Bideau, B., Delamarche, P., & Kulpa, R. (2016). Influence of a prolonged tennis match play on serve biomechanics. *PLoS ONE*, *11*(8), 1–14. https://doi.org/10.1371/journal.pone.0159979

Martin, C., Kulpa, R., Delamarche, P., & Bideau, B. (2013). Professional tennis players' serve: correlation between segmental angular momentums and ball velocity. *Sports Biomechanics*, *12*(1), 2–14. https://doi.org/10.1080/14763141.2012.734321

Martin, C., Kulpa, R., Ropars, M., Delamarche, P., & Bideau, B. (2013). Identification of temporal pathomechanical factors during the tennis serve. *Medicine and Science in Sports and Exercise*, *45*(11), 2113–2119. https://doi.org/10.1249/MSS.0b013e318299ae3b

Maurer, C., Stief, F., Jonas, A., Kovac, A., Groneberg, D. A., Meurer, A., & Ohlendorf, D. (2015). Influence of the lower jaw position on the running pattern. *PLoS ONE*, *10*(8), 1–16. https://doi.org/10.1371/journal.pone.0135712

McGinnis, R. S., Cain, S. M., Davidson, S. P., Vitali, R. V., Perkins, N. C., & McLean, S. G. (2016). Quantifying the effects of load carriage and fatigue under load on sacral kinematics during countermovement vertical jump with IMU-based method. *Sports Engineering*, *19*(1),

21–34. https://doi.org/10.1007/s12283-015-0185-3
Mehdizadeh, S., Arshi, A. R., & Davids, K. (2014). Effect of speed on local dynamic stability of locomotion under different task constraints in running. *European Journal of Sport Science*, *1391*(June 2015), 37–41. https://doi.org/10.1080/17461391.2014.905986
Menache, A. (2011). Understanding Motion Capture for Computer Animation. *Understanding Motion Capture for Computer Animation*, (2), 75–134. https://doi.org/10.1016/B978-0-12-381496-8.00003-2
Milanese, C., Corte, S., Salvetti, L., Cavedon, V., & Agostini, T. (2016). Correction of a Technical Error in the Golf Swing: Error Amplification Versus Direct Instruction. *Journal of Motor Behavior*, *48*(4), 365–376. https://doi.org/10.1080/00222895.2015.1102699
Mundy, P. D., Lake, J. P., Carden, P. J. C., Smith, N. A., & Lauder, M. A. (2016). Agreement between the force platform method and the combined method measurements of power output during the loaded countermovement jump. *Sports Biomech*, *15*(1), 23–35. https://doi.org/10.1080/14763141.2015.1123761
Nedergaard, N. J., Heinen, F., Sloth, S., Holmberg, H.-C., & Kersting, U. G. (2015). Biomechanics of the ski cross start indoors on a customised training ramp and outdoors on snow. *Sports Biomechanics*, *14*(3), 273–286. https://doi.org/10.1080/14763141.2015.1052543
Norcross, M. F., Lewek, M. D., Padua, D. A., Shultz, S. J., Weinhold, P. S., & Blackburn, J. T. (2013a). Lower extremity energy absorption and biomechanics during landing, part I: Sagittal-plane energy absorption analyses. *Journal of Athletic Training*, *48*(6), 748–756. https://doi.org/10.4085/1062-6050-48.4.09
Norcross, M. F., Lewek, M. D., Padua, D. A., Shultz, S. J., Weinhold, P. S., & Blackburn, J. T. (2013b). Lower extremity energy absorption and biomechanics during landing, part II: Frontal-plane energy analyses and interplanar relationships. *Journal of Athletic Training*, *48*(6), 757–763. https://doi.org/10.4085/1062-6050-48.4.10
O'Keefe, J. A., Orías, A. A. E., Khan, H., Hall, D. A., Berry-Kravis, E., & Wimmer, M. A. (2014). Implementation of a markerless motion analysis method to quantify hyperkinesis in males with fragile X syndrome. *Gait and Posture*, *39*(2), 827–830. https://doi.org/10.1016/j.gaitpost.2013.10.017
Otsuka, M., Ito, T., Honjo, T., & Isaka, T. (2016). Scapula behavior associates with fast sprinting in first accelerated running. *SpringerPlus*, *5*(1), 682. https://doi.org/10.1186/s40064-016-2291-5
Papi, E., Osei-Kuffour, D., Chen, Y.-M. A., & McGregor, A. H. (2015). Use of wearable technology for performance assessment: a validation study. *Medical Engineering & Physics*, *37*(7), 698–704. https://doi.org/10.1016/j.medengphy.2015.03.017
Pfister, A., West, A. M., Bronner, S., & Noah, J. A. (2014). Comparative abilities of Microsoft Kinect and Vicon 3D motion capture for gait analysis. *J Med Eng Technol*, *38*(5), 1464–522. https://doi.org/10.3109/03091902.2014.909540
Pueo, B. (2016). High speed cameras for motion analysis in sports science. *Journal of Human Sport and Exercise*, *11*(1), 53–73.
Pueo, B., Lipinska, P., Jiménez-Olmedo, J. M., Zmijewski, P., & Hopkins, W. G. (2016). Accuracy of Jump-Mat Systems for Measuring Jump Height. *International Journal of Sports Physiology and Performance*, 1–17. https://doi.org/10.1123/ijspp.2016-0511
Rantalainen, T., Hart, N. H., Nimphius, S., & Wundersitz, D. W. (2016). Associations Between Step Duration Variability and Inertial Measurement Unit Derived Gait Characteristics. *Journal of Applied Biomechanics*, *32*(4), 401–6. https://doi.org/10.1123/jab.2015-0266
Reid, M., Giblin, G., & Whiteside, D. (2014). A kinematic comparison of the overhand throw and tennis serve in tennis players: How similar are they really? *Journal of Sports Sciences*, *414*(January), 1–11. https://doi.org/10.1080/02640414.2014.962572
Ruffaldi, E., Peppoloni, L., & Filippeschi, a. (2015). Sensor fusion for complex articulated body tracking applied in rowing. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *229*(2), 92–102. https://doi.org/10.1177/1754337115583199
Sandau, M., Koblauch, H., Moeslund, T. B., Aanæs, H., Alkjær, T., & Simonsen, E. B. (2014). Markerless motion capture can provide reliable 3D gait kinematics in the sagittal and frontal plane. *Medical Engineering and Physics*, *36*(9), 1168–1175. https://doi.org/10.1016/j.medengphy.2014.07.007
Schmitz, A., Ye, M., Boggess, G., Shapiro, R., Yang, R., & Noehren, B. (2015). The measurement of in vivo joint angles during a squat using a single camera markerless motion capture system as compared to a marker based system. *Gait and Posture*, *41*(2), 694–698. https://doi.org/10.1016/j.gaitpost.2015.01.028
Schmitz, A., Ye, M., Shapiro, R., Yang, R., & Noehren, B. (2014). Accuracy and repeatability of joint angles measured using a single camera markerless motion capture system. *Journal of Biomechanics*, *47*(2), 587–591. https://doi.org/10.1016/j.jbiomech.2013.11.031
Sinclair, J., & Bottoms, L. (2013). Gender differences in the kinetics and lower extremity kinematics of the fencing lunge. *International Journal of Performance Analysis in Sport*, *13*(2), 440–451.
Sinclair, J., Currigan, G., Fewtrell, D., & Taylor, P. J. (2014). Biomechanical correlates of club-head velocity during the golf swing. *International Journal of Performance Analysis in Sport*, *14*(1), 54–63.
Sinclair, J., Fewtrell, D., Taylor, P. J., Atkins, S., Bottoms, L., & Hobbs, S. J. (2014). Three-dimensional kinematic differences between the preferred and non-preferred limbs during maximal instep soccer kicking. *Journal of Sports Sciences*, *32*(20), 1914–1923. https://doi.org/10.1080/02640414.2014.965188
Sinclair, J., Fewtrell, D., Taylor, P. J., Bottoms, L., Atkins, S., & Hobbs, S. J. (2014). Three-dimensional kinematic correlates of ball velocity during maximal instep soccer kicking in males. *European Journal of Sport Science*, *14*(8), 799–805. https://doi.org/10.1080/17461391.2014.908956
Skublewska-Paszkowska, M., Montusiewicz, J., £ukasik, E., Pszczo³a-Pasierbiewicz, I., Baran, K., Smo³ka, J., & Pueo, B. (2016). Motion Capture As a Modern Technology for Analysing Ergometer Rowing. *Advances in Science and Technology Research Journal*, *10*(29), 132–140. https://doi.org/10.12913/22998624/61941
Sommer, M., Häger, C., & Rönnqvist, L. (2014). Synchronized metronome training induces changes in the kinematic properties of the golf swing. *Sports Biomechanics*, *13*(1), 1–16. https://doi.org/10.1080/14763141.2013.873817
Southgate, D. F. L., Prinold, J. A. I., & Weinert-Aplin, R. A. (2016). Motion Analysis in Sport. In *Sports Innovation, Technology and Research* (pp. 3–30). World Scientific. https://doi.org/10.1142/9781786340429_0001
Telfer, S., Woodburn, J., & Turner, D. E. (2014). An ultrasound based non-invasive method for the measurement of intrinsic foot kinematics during gait. *Journal of Biomechanics*, *47*(5), 1225–1228. https://doi.org/10.1016/j.jbiomech.2013.12.014
Thewlis, D., Bishop, C., Daniell, N., & Paul, G. (2013). Next-Generation Low-Cost Motion Capture Systems Can Provide Comparable Spatial Accuracy to High-End Systems, *29*(1), 112–117.
Wang, F., Skubic, M., Rantz, M., & Cuddihy, P. E. (2014). Quantitative gait measurement with pulse-doppler radar for passive in-home gait assessment. *IEEE Transactions on Biomedical Engineering*, *61*(9), 2434–2443. https://doi.org/10.1109/TBME.2014.2319333
Yeung, L. F., Cheng, K. C., Fong, C. H., Lee, W. C. C., & Tong, K.-Y. (2014). Evaluation of the Microsoft Kinect as a clinical assessment tool of body sway. *Gait & Posture*, *40*(4), 532–538. https://doi.org/10.1016/j.gaitpost.2014.06.012
Zago, M., Piovan, A. G., Annoni, I., Ciprandi, D., Iaia, F. M., & Sforza, C. (2015). Dribbling determinants in sub-elite youth soccer players. *Journal of Sports Sciences*, *414*(March), 1–9. https://doi.org/10.1080/02640414.2015.1057210
Zhang, Y., Ma, Y., & Liu, G. (2016). Lumbar spinal loading during bowling in cricket: a kinetic analysis using a musculoskeletal modelling approach. *Journal of Sports Sciences*, *34*(11), 1030–5. https://doi.org/10.1080/02640414.2015.1086014
Zhang, Z., Li, S., Wan, B., Visentin, P., Jiang, Q., Dyck, M., … Shan, G. (2016). The Influence of X-Factor (Trunk Rotation) and Experience on the Quality of the Badminton Forehand Smash. *Journal of Human Kinetics*, *53*(1), 9–22. https://doi.org/10.1515/hukin-2016-0006
Zorko, M., Nemec, B., Babiè, J., Lešnik, B., & Supej, M. (2015). The waist width of skis influences the kinematics of the knee joint in alpine skiing. *Journal of Sports Science and Medicine*, *14*(3), 606–619.