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Method analysis of accelerometers and gyroscopes in running gait:

A systematic review

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Abstract

Purpose: To review articles utilising accelerometers and gyroscopes to measure running gait and assess various methodology utilised when doing so. To identify research and coaching orientated parameters which have been previously investigated and offer evidence based recommendations as to future methodology employed when investigating these parameters.

Methods: Electronic databases were searched using key related terminology such as accelerometer(s) and gyroscope(s) and/or running gait. Articles returned were then visually inspected and subjected to an inclusion and exclusion criteria after which citations were inspected for further relevance. Thirty-eight articles were then included in the review.

Results: Accelerometers, gyroscopes plus combined units have been successfully utilised in the generation of research orientated parameters such as head/tibial acceleration, vertical parameters and angular velocity and also coach orientated parameters such as stride parameters and gait pattern. Placement of sensors closest to the area of interest along with the use of bi/tri- axial accelerometers appear to provide the most accurate results.

Conclusion: Accelerometers and gyroscopes have proven to provide accurate and reliable results in running gait measurement. The temporal and spatial running parameters require sensor placement close to the area of interest and the use of bi/triaxial sensors. Post data analysis is critical for generating valid results.

Key Words

Accelerometry, gyroscopes, inertial measurement unit, kinematics, variability.

1. Introduction

While running continues to increase in popularity so too does the number of people suffering from Running Related Injuries (RRI)[1]. Injury incidence levels amongst runners have reached as high as 85% in recent research[2]. In an effort to combat RRI levels there has been increasing demand for running gait research. While previous methods of analysis have generally required well equipped research labs, recently there has been a move to produce low cost, portable equipment. This allows researchers to remove participants from an artificial laboratory environment, to measure participants in a more natural environment and uncover longitudinal information perhaps more applicable to real life practice[3]. With this the use of accelerometers and gyroscopes has increased. These devices 'exploit the property of inertia, i.e. resistance to a change in motion, to sense angular motion in the case of the gyroscope, and changes in linear motion in the case of the accelerometer'[4]. Scientists have also discovered their potential in assessing gait analysis without the restrictions of laboratory technology[5]. In addition, research has shown that typical observational kinematic measurement systems, such as video analysis techniques often employed by coaches are wholly subjective and based on the knowledge of the coach[6] and that coaches accuracy at scoring the same movement recorded using video analysis changes over time[7]. Therefore accelerometers and gyroscopes are also bridging a gap between coaching and science performance measures providing research orientated parameters (acceleration, velocity) and coach orientated parameters (stride length, stride frequency). These parameters, both alone and combined, have in the past been linked to RRI[8]. The evolution of these sensors for biomechanical analysis has gathered pace as they provide direct contact with the subject in question, whilst also becoming smaller in size and more wearable, allowing for use during more dynamic movement[9]. MEMS (microelectromechanical systems) accelerometers have led the way in technology for direct measurement of acceleration. While previous optical measurement systems allow for acceleration calculation error, during the differentiation of displacement and velocity measurements (such as 2D image analysis), accelerometers avoid this while also having the benefit of utilising one or multiple axes[3]. This has led to accelerometers being successfully validated for identifying a number of parameters when measuring running gait including centre of mass (COM) vertical displacement[10], stride parameters and running speed[11], and angular velocity[12]. Similar to accelerometers, gyroscopes are portable, lightweight and provide direct measurement, in this case, of angular velocity. Gyroscopes when combined with accelerometers form a very useful, compact measurement system, an inertial measurement unit (IMU), which have also been successfully validated in identifying parameters when measuring running gait including stride times[13], vertical displacement[14] and speed[15]. While there has been much evidence to support the validity of accelerometers and gyroscopes in measuring running gait there is still debate regarding the techniques used while utilising these systems. A previous systematic review[16] focused on the implementation and data processing of the sensors (i.e. study design, fixation) however that review focused only on lower limb kinematics and also included a range of activities including walking, sitting and tennis serving. While that review may aid researchers in considering implementing this analysis method across a range of activities it does not divulge critical information as to the direct methodology when performing movement at high velocity, as done in running. It is also necessary that this information is made accessible both to the science community and to running coaches, so it can be accessed by the running population. Therefore a systematic review is necessary so that a summary of information will be collated from which biomechanists and coaches alike will be able to make educated decisions about the appropriate methods of the application of accelerometers and/or gyroscopes to assess running gait. While in this review accelerometers, gyroscopes or combined units (IMU) will be included accelerometers will feature more heavily due to their greater popularity in running gait analysis. Regardless, from the information gathered here it is hoped in the future that scientists and coaches alike will be able to successfully identify kinematic parameters from sensor data, which may be linked with RRI.

2. Research Methods

PubMed, ScienceDirect, Web of Knowledge and Google Scholar were searched to identify studies which utilised accelerometers and/or gyroscopes for running gait kinematic analysis. Searches consisted of a combination of the following keywords (1) inertial sensors or accelerometer/s or acceleration or gyroscopes or wearable sensors or sensing technology or inertial measurement unit and (2) gait or locomotion or running or running gait. Due to recent technology advances articles within the last decade were preferentially considered.

The inclusion criteria for study selection were (1) the literature was written in English (2) participants were human (3) sensors consisted of accelerometers or gyroscopes individually or when combined within one unit (IMU) (4) participants performed running gait whilst wearing the sensors and (5) clearly defined outcome measures were kinematic parameters. Articles which did not meet the inclusion criteria after inspection of the title and abstract were omitted. Reference lists of articles which met the inclusion criteria were then physically searched to identify any potentially relevant articles which may not have been identified in the previous search. A total of 38 articles were identified (See Figure 1).

3. Results

In the 38 articles 385 participants (166 distance runners, 12 sprinters, 144 recreational runners and 63 mixed sport or unknown) were tested with a mean of 10.1 ± 7.8 participants per study. These participants performed on average 3.8 ± 3.9 trials from which accelerometer and/or gyroscope data were used, with a total of 1488 trials completed. Of the 38 articles only 10 articles[13-15, 17-23] utilised IMU's, with combined accelerometer and gyroscope capabilities, while the remaining 28 utilised either accelerometers or gyroscopes individually.

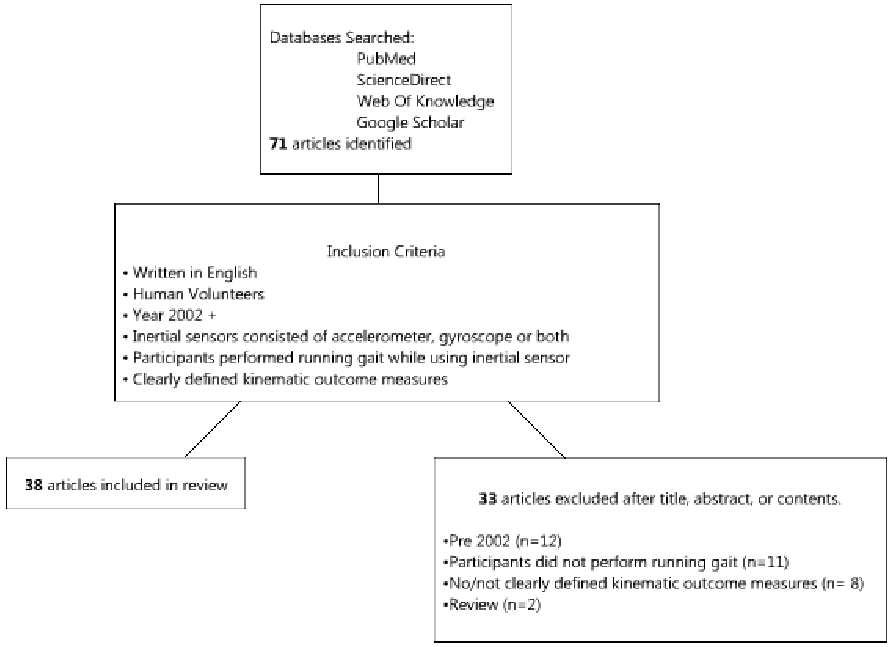

Figure 1. Flow chart describing the selection and exclusion of articles.

3.1 Research orientated kinematic output parameters

Of the 38 articles included in the review 23 utilised accelerometers and/or gyroscopes during running gait to derive research orientated kinematic parameters (See Table 1.1).

3.1.1 Tibial/shank acceleration. Firstly shank/tibial acceleration was identified in 12 of the 23 articles (See Table 1.1). Peak tibial acceleration after impact was identified in all 12 studies which may be due to its links with overuse injury such as tibial stress fractures[28, 39]. All but 1 of the 12 studies generated peak tibial acceleration data by attaching the accelerometer to the distal anteromedial portion of the tibia. Clark et al.[27] placed their accelerometer on the proximal tibial tuberosity. Although research has indicated that the distal anteromedial portion of the tibia is chosen as a placement site to reduce the effect of angular acceleration and rotational movement[30], Clark et al.[27] were not incorrect in their placement. Clark et al.[27] were interested in tibial acceleration at the knee, of most importance in the mediolateral plane, as they investigated varus/valgus knee motion during running. By placing the accelerometer at the proximal end of the tibia Clark et al.[27] were following protocol in line with Mathie et al.[40] which states that accelerometer placement is key to providing accurate output and should be placed on the area of interest. Clark et al.'s[27] study also led them to being the only study of the twelve which identified tibial acceleration in all three planes, vertical, mediolateral and anteroposterior, which has been previously identified as an area to be investigated due to high acceleration rates within these planes[41]. While their study may provide important information on knee movement one flaw can be identified, which is the size of the accelerometer used. When comparing bone and skin mounted accelerometers, while bone was found to be more accurate skin mounted were found to be acceptable as long as the mass of the accelerometer was kept minimal, <3g suggested[42]. The accelerometer used by Clark et al.[27] weighed 25g, over eight times the suggested mass, which may have led to spurious data, in all planes. For the remaining articles six utilised accelerometers weighing more than 3g[1, 26, 30, 34, 35, 39] which question the validity of their results. Three studies utilised accelerometers weighing less than 3g[24, 29, 36] and one[28] did not outline the mass of the accelerometer used. It is also important to note that the majority of the 12 studies identified peak tibial acceleration utilising uni-axial accelerometers (n=8) which, despite producing sufficient peak tibial acceleration data, has limitations.

Table 1.1 Research orientated kinematic output article details.

	Abt et al.[1]	Bergamini et al.[17]	Butler et al.[24]	Channells et al.[12]	Clansey et al.[25]	Clansey and Hanlon[26]	Clark et al.[27]	Crowell et al.[28]	Derrick et al.[29]	Gullstrand et al.[10]	Laughton et al.[30]	Le Bris et al.[31]	Lee et al.[32]	Lee et al.[5]	McGregor et al.[33]	Mercer et al.[34]	Mercer et al.[35]	Mercer et al.[36]	Milner et al.[37]	Patterson et al.[38]	Stohrmann et al.[22]	Stohrmann et al.[23]	Tan et al.[14]
Tibial/Shank Acceleration	·		·		·	·	·	·	·		·					·	·	·	·				
Head Acceleration	·				·	·			·							·	·	·					
Shock Attenuation	·					·			·							·	·	·					
Vertical Parameters										·			·	·							·	·	·
Angular Velocity		·		·																			
Stride Regularity /Symmetry												·											
Accelerometry relative to Vo2 and speed															·								
Total Acceleration and Kinematic Patterns																				·			

Mercer et al.[34] reported that when the subject was standing the axis of the accelerometer was aligned with the longitudinal axis of the tibia however with any manipulation of stride length, as can happen in fatiguing long distance running, the axis alignment became distorted. Although previous research has stated that this misalignment leads to minimal differences in acceleration values (1-2% impact peak magnitude)[43] the risk of this affecting data could be minimised with the use of bi-axial and tri-axial accelerometers. Four studies[29, 34-36] also analysed tibial acceleration across the stance phase using the Fast Fourier transformation function to calculate power spectral density (PSD) using a previously published method[44]. Using the aforementioned methods tibial acceleration has been successfully identified to be reduced in high arched runners when running in cushion trainers shoes compared to motion control shoes[24] and also decrease when provided as visual feedback to those running on treadmills[28]. Tibial acceleration was also found to be increased in fore-foot strikers opposed to rear foot strikers[30] and identified to increase mediolaterally in women during menstruation compared to ovulation[27]. Lastly it has been found to increase with increases in preferred stride length[34] and showed mixed increases when investigated in relation to fatiguing runs (dependent on run length and training status of runner)[1, 25, 29, 35, 36, 39].

3.1.2 Head acceleration. A second variable of interest was head acceleration which was successfully identified in 7[1, 26, 29, 34-36, 39] of the 23 articles which examined research orientated kinematic parameters. Head acceleration has been identified due to its role in understanding shock absorption as the body attempts to combat the repetitive forces being applied to it during running[26]. All seven studies outline that to acquire head acceleration data the accelerometer was placed on the anterior aspect of the forehead [34] or the frontal bone of the skull[29] whilst all seven also provided extra strapping or adhesive to ensure attachment. Head peak impact acceleration was the key parameter investigated in all 7 studies with 4 of the studies[29, 34-36] also generating the PSD value for head acceleration during stance. Head acceleration values were successfully acquired within all seven studies with no limitations identified (as regards to attachment point or output data). Using accelerometry to analyse head movement has therefore led to information being derived such as knowledge that PSD_{head} remains between a narrow magnitude when stride length or frequency is adapted, without inducing fatigue[35]. Also accelerometry data has found that PSD_{head} and peak impact head accelerations can significantly increase[26] or remain relatively consistent[29, 35] after fatiguing runs. This, as before, may be due to varying conditions within the different studies such as test design (i.e. length of run) and training status of runners playing a role, with Hamill et al.[45] believing that at high speed constant head acceleration is needed to maintain visual field[36]. Alternatively longer fatiguing runs that altered joint mechanics due to increased fatigue can have a greater impact, perhaps even in more highly trained athletes[39].

3.1.3 Shock attenuation. Shock attenuation is the process of decreasing the magnitude of impact force between the leg and head and is derived from the accelerations of these segments.

It was another variable commonly looked at within the 12 articles containing research orientated kinematic parameters. It was identified in 6 of the 12 articles and is important considering the repetitive nature of running thus any alteration of the body's ability to absorb shock could lead to additional stresses being placed on joints and the onset of overuse injury[1]. Four of the six articles[1, 29, 34, 35] calculated shock attenuation using the same transfer function utilising frequency domain analysis. All of these articles identified shock attenuation as the average transfer function across similar impact frequencies ranges (10-20 Hz for Abt et al.[1], Derrick et al.[29] and Mercer et al.[34], 11-18 Hz for Mercer et al.[35]). This method resulted in a shock attenuation value in decibels, with positive values indicating a gain in the acceleration signal from leg to head and negative values indicating attenuation of the signal. Of the two remaining articles, however, while one study utilised a simplified frequency domain analysis of ratio of PSD_{head} to PSD_{leg} (with a low ratio indicative of greater attenuation)[36] the other utilised time domain analysis using averaged peak head and tibial accelerations[26], shown in Equation 1.

$$\text{Shock attenuation} = \left(1 - \frac{\text{peak head acceleration}}{\text{peak tibial acceleration}}\right) \times 100 \qquad (1)$$

Although these methods generate a numeric value representative of shock attenuation it is thought the preferred method is using the PSD and Four Fourier technique followed by the average transfer function. This analysis of the frequency domain allows us to attain greater understanding of the distribution of the energy in the signal, in this case acceleration, and also can let us see how quickly shock attenuation can occur. Within the 6 articles, 3 articles[29, 34, 36] identified shock attenuation increases, all utilising the average transfer function value at similar running impact frequencies. Whilst Derrick et al.'s[29] study was based on an exhaustive run Mercer et al.[34] and Mercer et al.[36] altered running conditions (stride length and frequency and speed), but commonly all three articles found an increase in stride length as well as shock attenuation. This link between shock attenuation and stride length is supported by Mercer et al.[35] who found decreases in shock attenuation post fatigue, but also consistent stride length pre and post. Similarly, Abt et al.[1] and Clansey and Hanlon[26] also found decreases in shock attenuation following fatiguing runs and indicate this is due to a highly trained population, who perhaps do not adapt stride length when facing fatigue due to enhanced coping strategies.

3.1.4 Vertical parameters. Vertical acceleration, displacement or vertical oscillation was also identified in 6 of the 23 articles[5, 10, 14, 22, 23, 32]. When measuring vertical oscillation 5 of the 6 articles located the accelerometer[5, 10, 32] or IMU[22, 23] in proximity to the centre of mass, placing it either on/near the sacrum[5, 10, 32] or located on the hip[22, 23] in order to give a true reflection of vertical displacement. On the other hand Tan et al.[14] attached their GPS/IMU system to the top of a cyclist's helmet which was worn by the runner. **This GPS/IMU unit combined GPS (global positioning systems) capabilities of determining speed over ground and an IMU (inertial measurement unit) comprised of an accelerometer, gyroscope, 3D magnetometer and temperature sensor[14]. Placement on top of the helmet** was for convenience as the system was bulky and required the mounting of an antenna, as did the GPS system it was being compared to (OEM4, Novatel, Canada). Also in Tan et al.'s[14] study when compared to the GPS system (OEM4) the combined **GPS/IMU** system achieved a reliability of 0.02 m in vertical displacement. Given this relatively large systematic error and the author's statement that the error was as a result of both measurements containing error neither of these two systems would be recommended for future measurement of vertical displacement. Of the remaining articles Lee et al.[32] found accelerometry acceptable in generating vertical acceleration in a transtibial amputee sprinter and Lee et al.[5] also found near perfect correlations and very small error between COM vertical acceleration when derived from an accelerometer and compared to 3D motion capture. This would indicate accelerometry as a highly valid method of deriving vertical COM parameters. However, while this level of validity is supported by Gullstrand et al.[10], when compared to three-dimensional infra-red motion capture and position transducers the reliability of the accelerometer is seen to be very poor as it produces a large amount of random error (5, 7 and 11 mm). Gullstrand et al.[10] however put this error down to changes in the orientation of the uniaxial accelerometers used. Although this was assumed to be constant the orientation was most likely altered at each step. Their suggestion for more complex sensors to be used to avoid this is supported by Lee et al.[5] as they used a triaxial accelerometer and their data did not suffer from this orientation alteration and therefore had small typical error (1.84 m/s^2). Of the studies which chose to analyse vertical displacement as opposed to acceleration[10, 22, 23] all studies double integrated the vertical acceleration component derived at the hip/sacrum. By using the above methods previous research has identified symmetry in running gait[5], examined the validity of accelerometers in assessing vertical parameters[5, 10, 14] and shown that there is little difference between vertical acceleration in anatomical and prosthetic strides[32]. Previous studies have also found conflicting results as to levels of vertical oscillation, dependent on running ability[22, 23].

3.1.5 Angular velocity. While most of the variables identified within this review so far have been linked to acceleration patterns 2 of the 28 articles identified also looked at angular velocity whilst running. Bergamini et al.[17] utilised an IMU consisting of a tri-axial accelerometer and a tri-axial gyroscope placed on the lower back (L1) to provide analysis of amateur and elite sprinters. They found that acceleration and angular velocity profiles provided no consistent features which could be linked to foot strike and toe off, which is in contrast to previous research using lumbar based sensors[46, 47]. It is thought Bergamini et al.'s[17] results may be due to utilising sprint trials in their study, which due to forefoot striking causes increased dampening of impact forces, making identifiable markers harder to distinguish. This raises the question whether lower back attached sensors are suitable for measuring sprint parameters. In contrast to this however Bergamini et al.[17] was able to identify consistent events on the second derivative of angular velocity wavelet, which verified that not only is trunk rotation present in sprinting, as had been previously found in walking and long distance running, but also that this feature could be found across different levels of athletes (amateur and elite) and could be utilised to identify stride duration. Negative and positive peaks related to time of heel strike and toe-off were also found on this wavelet. While Bergamini et al.[17] utilised gyroscopes within an IMU to identify angular velocity patterns, Channells et al.[12] utilised accelerometry data which were then integrated. They placed an acceleration measurement unit (AMU) consisting of 2 bi-axial accelerometers (one measuring mediolateral and anteroposterior accelerations – x and y axis, the second measuring vertical accelerations - z axis) on the athlete's shin with which they then performed a series of walking, jogging and running trials. Angular velocity data were then generated through integration which were compared to angular velocity derived through the same calculation using motion capture. They found that the AMU resulted in comparable angular velocity patterns when compared to the motion capture and this was not affected by running technique. It was, however, affected by running speed; results indicating that as speed increased so did error (percentage error ranges from 2.31% in walking to 9.76% at higher speeds). This increase in error could be due to increasing noise induced integration error due to poor attachment at increased speeds. Both papers found increased problems when looking at angular velocity during sprinting and so may raise the question as to techniques used by both studies. Perhaps combining the equipment used by Bergamini et al.[17] based on its high validity and gyroscope utilisation, and the tibial attachment site (used by Channells et al.[12]) should be further investigated when analysing angular velocity in sprinting.

3.1.6 Remaining parameters. Having identified the common themes within the 38 articles investigating research orientated kinematic parameters there were 3 papers which identified unique variables[31, 33, 38] utilising accelerometers. Le Bris et al.[31] investigated the effect of fatigue on middle distance runner's stride patterns using the Locometrix system (Locometrix™, Centaure Metrix, France) located on the lower back. While they looked at stride regularity (similarity of cranial-caudal acceleration over successive strides) and stride symmetry (similarity of cranial-caudal acceleration over left and right strides) through autocorrelation, these variables are similar to those found by papers looking at vertical acceleration[5, 10, 14, 22, 23, 32]. Of greater interest however was their use of accelerometry in the investigation into medio-lateral axis acceleration patterns. While this is similar to that done by Clark et al.[27] in their investigation of knee varus/valgus movement, Le Bris et al.[31] located their accelerometer on the centre of the lower back, close to the COM, which gives a better indicator of whole body movement as affected by fatigue. From this they found that fatigue increased the medio-lateral impulse significantly in sub-elite middle distance runners, perhaps indicating they cannot combat fatigue as effectively as elite, leading to increasing energy expenditure in an axis (mediolateral) not conducive to propulsion. McGregor et al.[33] also investigated kinematic accelerometry patterns by locating an accelerometer on the lower back of their participants; however they wished to investigate the validity of using the accelerometer relative to Vo2 and speed by comparing the root mean square of the three axes and the Euclidean resultant (RES) to Vo2. They not only found that the accelerometer was highly valid and reliable in predicting Vo2 but also looked to investigate the differences between trained and untrained runners in regards to acceleration at certain speeds, economy of acceleration relative to speed and ratio of accelerations relative to RES in all axes. By using the acceleration data derived from their trials in this manner McGregor et al.[33] were able to divulge a wealth of information regarding acceleration pattern differences between trained and untrained runners performing to fatigue. They found that nearly all acceleration parameters were lower in trained than untrained runners perhaps indicating enhanced running economy when reaching fatigue (through positive adaptions), which is supported through much of the research[1, 26], supporting the validity of their study. Lastly Patterson et al.[38] looked at acceleration of the lower limb by placing a tri-axial accelerometer on the shoe laces of their subject. From this they wished to investigate the relationship between the total acceleration, x and y axis accelerations and kinematic gait movements such as knee and ankle angle at various parts of the gait cycle (initial swing, mid-swing) during fatiguing runs. They were able to identify certain relationships existed, such as accelerometer variables during mid-swing being predictive of dorsi-flexor fatigue. However their study was only performed on one subject and so these results are not necessarily generalizable to a larger population, given that gait has such individual characteristics.

3.2 Coach orientated kinematic output parameters

Having investigated research orientated kinematic parameters identified using accelerometers and/or gyroscopes it was also important to investigate coach orientated parameters. This is to ensure that these sensors were able to generate information accessible to audiences of different scientific knowledge backgrounds. Of the 38 articles included in this review 23 articles utilised accelerometers and/or gyroscopes during running gait to identify coach orientated kinematic parameters (See Table 1.2).

Table 1.2 Coach orientated kinematic output parameters

	Auvinet et al.[48]	Bergamini et al.[17]	Bichler et al.[18]	Cooper et al.[19]	Hausswirth et al.[11]	Heiden et al.[49]	Le Bris et al.[31]	Lee et al.[32]	Lee et al.[47]	McCurdy et al.[50]	McGrath et al.[13]	Mercer et al.[35]	Mercer et al.[36]	Neville et al.[51]	Neville et al.[52]	O'Donovan et al.[20]	Purcell et al.[53]	Stohrmann et al.[22]	Stohrmann et al.[21]	Stohrmann et al.[23]	Tan et al.[14]	Wixted et al.[54]	Yang et al.[15]
Step/Stride Frequency			•		•		•			•		•	•	•	•					•	•		
Temporal Parameters		•	•					•	•		•					•	•	•	•	•			
Gait Pattern	•					•																•	
Step/Stride Length			•							•		•	•										
Foot Strike Type																	•		•	•			
Heel Lift																			•	•			
Speed					•																		•
Knee Angle				•																			
Sprint Time										•													
Upper Body Parameters																				•			

3.2.1 Step/stride frequency/rate. Firstly frequency or rate of step and stride, was commonly identified in 10 of the 38 articles[11, 14, 18, 23, 31, 35, 36, 50-52]. Stride frequency is important as increased stride frequency means increased repetitive impacts on the body which can lead to a higher risk of injury and degenerative disease due to increased stress on the structure of the body[45]. Of the 10 articles 4 articles did not define how they identified step/stride frequency[11, 14, 31, 50] with some only identifying that it was analysed using the Fast Fourier Transform via MATLAB[31]. Of the remaining 6 articles however 5 identified stride frequency using similar methods. Mercer et al.[36] and Mercer et al.[35] identified the peak in vertical acceleration associated with foot impact and calculated stride frequency as a result of the time, whilst Stohrmann et al.[23] identified peak impact by not only looking at the anterior-posterior acceleration curve but combining the three planes of acceleration to calculate the magnitude. All three studies chose lower limb sensor attachment and whilst Stohrmann[23] utilised an IMU all three papers identified results through accelerometer generated data. Neville et al.[51] and Neville et al.[52] again utilised accelerometer sensors combined with a zero crossing method in MATLAB (not dissimilar to the previously mentioned method). Here every zero crossing in the anterior-posterior plane was identified as a foot impact, which was then divided by the time between first and last impact to derive stride frequency. As there would be minimal time difference in the time of zero crossing and impact peak and both methods successfully derived stride frequency both methods could be used. However, the zero crossing method was successfully compared to speed as measured using a stopwatch (stride frequency showing a linear trend as speed increase, r^2=0.896) and GPS (r^2=0.901)[52] and against various speeds as measured by GPS (walking – $r^{2=}$.0820, running r^2=0.838[51]). This supports its position as the method with proven validity. It is important to note, however, the use of a stopwatch as a comparison speed measurement device. This method is highly subjective and has been found to be a valid method in assessing speed only when used by a trained tester[55]. It is not stated in Neville et al.[52] whether the tester is trained or not, which may question the derived speed accuracy. While it could be argued that Neville et al.[51, 52] placed their accelerometers on the lower back, against that recommended by Mathie et al.[40], foot strike here created easily identifiable makers in large peak acceleration changes and so was identifiable regardless of position. This is in contrast to that found by Bergamini et al.[17] who utilising an IMU were unable to identify a regular pattern on the acceleration curve using the same sensor placement. However, in Bergamini et al.[17] the subjects sprinted, which is thought to have hindered pattern identification. Lastly, in terms of identifying stride frequency, Bichler et al.[18] utilised an IMU, however unlike Bergamini et al.[17] and Stohrmann et al.[23] they utilised the gyroscope data available to identify stride frequency. They expanded the "pedestrian dead reckoning" method (a method used to give position and orientation of a subject using integration of acceleration and angular velocity – Torres-Solis and Chau[56]) to provide greater accuracy during running. This method identified the rotation of the foot prior to, during and after stance in order to derive stride parameters such as stride frequency. From this stance could be identified due to rotation below a certain threshold (<1 rad/s) and also with combined accelerometer key markers (peak at impact)[18]. When this method was compared to video analysis it was found to show a more regular pattern in terms of stride frequency but also that increases in speed increased parameter failure rate. However these differences between measurement systems (IMU/GPS and video) overall were minimal and most lay within 95% limits of agreement. Any differences could also be due to the weak comparison method of 2D analysis and also stance would have been identified here as ground contact time, as opposed to with the sensor data where it was identified by level of rotational movement. By using the above methods, the use of accelerometers and/or gyroscopes to derive stride frequency has been validated[11, 14, 51, 52] and also been successfully used to derive stride frequency changes with speed[36], fatigue[23, 31] and its relationship to jump performance[50].

3.2.2 Temporal parameters. Secondary coach orientated kinematic parameters which were identified were temporal and covered a multitude of smaller parameters. Parameters which included foot/ground interface (foot contact time, step, stance and stride duration) and also airborne parameters such as swing time were identified through use of accelerometers and/or gyroscopes in 10 of the 24 articles[13, 17, 18, 20-23, 32, 47, 53]. In order to identify these parameters all the studies required identification of when the foot was in contact with the ground through knowledge of when foot strike occurred and toe-off occurred. Utilising an IMU Stohrmann et al.[21, 22] identified foot/ground contact through an acceleration threshold, where below 2g (g=gravity) represented stance time with values increasing above this representing swing time. This use of a threshold is commonly seen in comparison analysis when using force plates[17, 53] but Stohrmann et al.[21, 22] is the only identified study to utilise it with accelerometry data. A more commonly identified method to generate foot contact times was by analysis of the anterior-posterior accelerometry data with positive peaks identifying foot strike and smaller peaks identifying toe-off[17, 32, 47, 53]. This method can provide information easily as it can be generated through visual observation of acceleration patterns, as done in Lee et al.[32]. The validity of this method has also been tested over differing conditions including a Paralympic sprinter using a prosthetic limb, and at varying running speeds with similar results[47, 53]. Lee et al.[47] found that an accelerometer based sensor placed on the lower back had strong agreement and near perfect correlations (r=0.90+) to 3D motion capture, for most parameters (step, stride and stance times) at varying running speeds (low, medium and high). This was similar to Purcell et al.'s[53] findings when comparing tibial accelerometry contact time measures to force plate data (r=0.89+). Gyroscope data derived from IMU units were also utilised to measure temporal parameters with O'Donovan et al.[20], Bichler et al.[18] and McGrath et al.[13] all identifying foot/ground interface using angular velocity. All three studies identified different methods to analyse angular velocity for ground contact. O'Donovan et al.[20] used a method by Aminian et al.[57] which utilised medio-lateral angular velocity. Bichler et al.[18] stated that foot contact occurred between the first and last samples of angular velocity below 1rad in the respective foot and McGrath et al.[13] utilised an algorithm which calculated thresholds based on angular velocity about the y- axis (mediolateral) and also incorporated an artefact rejection routine. Two of the 3 studies validated their methods in comparison to 3D motion capture with Bichler et al.[18] identifying their 2D camera analysis as a limitation to their study, perhaps being too weak for a comparison method and leading to poorer results with Intra-class coefficient (ICC) results here (averaged 0.4) being lower than both O'Donovan et al.[20] (0.86) and McGrath et al.'s[13] (0.53 +) findings. When looking at the individual parameter findings McGrath et al.[13] showed poor to moderate ICC (0.24 -0.66) for stance and swing times across all speeds when comparing gyroscope data to motion capture. This is in contrast to O'Donovan et al.[20] who found high ICC values (0.85 and 0.99) for these parameters, although a major difference here is that O'Donovan et al.[20] utilised both walking and jogging and did not differentiate the results of both or state the speeds utilised. Therefore the higher values represented by O'Donovan et al.[20] could be due to slower speeds, which is supported by the fact that ICC values at the top of McGrath et al.'s[13] range for swing and stance time utilising gyroscopes were closer to O'Donovan et al.'s[20] values (0.66 compared to 0.99 for stance time). Overall, studies which utilised gyroscopes all demonstrated limitations or require further study in the validation of this method so accelerometer data may be a more valid method of analysis in temporal parameters. In general studies which have utilised the above methods have investigated changing temporal parameters regarding fatigue[23], in sprinting kinematics with the use of a prosthetics limb[32] and in the validity of accelerometers and/or gyroscopes as a measurement technique[17, 18, 53].

3.2.3 Gait pattern. Gait pattern was also identified in 3 of the 24 articles which examined coach orientated parameters[48, 49, 54]. All three studies utilised accelerometers and wished to identify key markers of gait pattern such as the acceleration peaks at foot strike and toe off to confirm that accelerometry was feasible for gait pattern analysis. Two of the studies compared accelerometric measures to force measures, with Heiden et al.[49] using force plate data as a comparison and Wixted et al.[54] using insole shoe sensors. While Heiden et al.[49] did not discuss comparison results, Wixted et al.[54] found by visual observation that accelerometer data showed a significant negative peak in the anterior-posterior plane which occurred at the approximate same time as heel strike, as shown by the insole shoe sensors. The end of foot contact, the period directly after toe off, was then characterised by vertical acceleration crossing zero positively, as foot contact and sensor pressure data ceased. Unfortunately no analysis was done on the timing of these events relative to one another and so it is not possible to compare these data to previous validation studies. Auvinet et al.[48] also employed visual comparison of gait pattern derived from accelerometer data (peaks in anterior-posterior and vertical planes) and, in this case, 2D motion capture data and once more found a deceleration trough in the anterior-posterior plane at foot strike with loading (zero crossing) at toe-off, same as Wixted et al.[54] found. Of most interest in these three articles was Heiden et al.'s[49] investigation as to whether the hip sensor or ankle sensor presented the most accurate data for gait pattern markers (heel strike and toe off). They reported that the hip sensor resulted in gait pattern data that could not lead to accurate and easily identifiable gait markers whereas the ankle sensor generated replicable and identifiable data. This supports Mathie et al.'s[40] thoughts on sensor location but contrasts with findings by Lee et al.[47] and Bergamini et al.[17]. Both Lee et al.[47] and Bergamini et al.[17] utilised lower back placement and successfully identified gait pattern. Although Bergamini et al.[17] did so using the second derivative of angular velocity and it is possible Lee et al.[47] did so at increased velocities compared to Heiden et al.[49], which they identified led to increased accelerometer peaks and easier identification. When using a lumbar sensor to derive gait pattern perhaps Lee et al.[47] utilised the best running speed (range 2.8-5.3 m/s) as they successfully validated this method in comparison to Heiden et al.[49] (unknown speed) and Bergamini et al.[17] (range 5.7-10.8 m/s) who at increased speeds found signal was dampened and markers on the accelerometer curve were unidentifiable. Easily recognised identification of gait pattern, as seen in these three studies, provides information on basic running pattern important to coaches.

3.2.4 Stride/step length. Another parameter identified via accelerometers and/or gyroscopes was stride/step length, identified in 4 of the 23 articles[18, 35, 36, 50]. Stride length is a key parameter for coaches as it provides information on fatigue and also has been linked with RRI in relation to lower limb stiffness[58]. While McCurdy et al.[50] did not discuss how stride length values were obtained, only that it was done so using an accelerometer attached to a waist belt, both Mercer et al.[36] and Mercer et al.[35] utilised the same method, dividing treadmill speed by already attained stride frequency (as previously discussed). All 3[35, 36, 50] of these articles utilised accelerometers in attaining stride/step length whilst Bichler et al.[18] utilised IMU derived gyroscope data also. Whilst outlining the advanced pedestrian dead reckoning method which Bichler et al.[18] used to derive kinematic parameters, does not specifically outline the method for calculating stride length, although results show that when compared to 2D camera analysis the mean stride length calculated by the IMU differed by only 0.01 m. This parameter was most sensitive to difference at higher speeds. Within these studies accelerometers and/or gyroscopes have uncovered stride length increases with increased velocity[36], unchanged stride length values after a graded exercise test[35], the relationship between stride length and jump performance in soccer players[50] and has also been validated to derive stride length at lower speeds[18]. However, as Bichler et al.[18] was the only author to test the validity of stride length results generated, and this was from gyroscope data, this is an area requiring further study.

3.2.5 Various remaining parameters. Other parameters identified are foot strike type[21, 23], heel lift[22, 23], running speed[11, 15], knee angle[19], sprint time[50] and arm movement, trunk forward lean and shoulder rotation[23]. Although measurements such as angle derivation and speed may not be commonly identified using accelerometers and/or gyroscopes this information does provide insight into advancing capabilities of these low cost transducers whilst also providing support for their validity within this research.

4. Recommendations for future research

4.1 Parameter specific recommendations

For researchers who intend to utilise accelerometers and/or gyroscopes for research and coach orientated kinematic parameters for running gait there are several recommendations. Firstly regarding research orientated kinematics there are recommendations when investigating tibial acceleration, head acceleration, shock attenuation, vertical parameters and angular velocity among some parameters. In terms of tibial acceleration it is recommended to follow guidelines as suggested by Mathie et al.[40] (placement closest to the area of interest), with accelerometer placement at the anterior/distal aspect of the tibia if tibia acceleration or running patterns derived from acceleration curves are of interest. It is also recommended that a bi-axial or tri-axial accelerometer is used as axial alignment has been found to become distorted during testing[34] and by having multiple axes to analyse this may have less of a negative effect on data collection. Sensor/device weight also plays an important role and it is recommended for accurate data collection to keep weight to <3g. This may be of vital importance especially in collecting tibial acceleration data as the sensor will be placed in a body segment of small surface area (distal tibia compared to lower back placement) and by keeping sensor weight low this will maximise the unobtrusive method of data collection. Secondly, in terms of head acceleration, recommendations on placement follow those of Mathie et al.[40] and so anterior aspect of the forehead is suggested and has been proven to be successful. This placement however can be the most obtrusive as the attachment of a foreign object onto the centre of a subject's forehead may be uncomfortable and unwanted during running. It is therefore suggested that this placement may be of the least value, as it obtains information only on shock attenuation and head acceleration and also may have the greatest effect on running efficiency and economy depending on the subject.

Recommendations in terms of collecting vertical parameter data using accelerometers and/or gyroscopes were also generated and again sensor location was recommended closest to the area of interest, the subject's centre of mass (lower back) for valid results. Also bi-axial or tri-axial accelerometers were recommended as altered orientation had again been observed and stated as a limitation using uni-axial accelerometers[10]. For angular velocity both accelerometers and gyroscopes have been utilised successfully however placement has proven to be vital as lumbar placed sensors were found to produce inconsistent patterns in relation to acceleration and angular velocity peaks and dips associated with gait, making it difficult to identify parameters in subjects performing a sprint. In contrast when accelerometers on their own were utilised, while attached to the distal tibia, consistent patterns were found, although error within these patterns increased with speed. It is therefore recommended that a combination of methods is utilised in the future to generate angular velocity data, especially for sprinting analysis. The utilisation of gyroscopes, as used by Bergamini et al.[17], to provide reliable data, followed with placement used by Channells et al.[12] is therefore recommended for future study. While these are the main research orientated kinematic parameters, accelerometers have also been proven to generate reliable data in the mediolateral planes when located at various attachment points. When attached to the proximal tibia, accelerometers have been found to generate knee valgus/varus data[27] and when attached to the lower back have generated running efficiency data[31]. This provides support for future studies not only investigating cranial-caudal and anteroposterior planes but also mediolateral to divulge important information.

In terms of generating coach orientated kinematic parameters through accelerometer and/or gyrscope utilisation there are also a number of recommendations. With stride frequency, identification has been successful using both the zero crossing method and identifying the peak in the anteroposterior acceleration curves. Also, whilst stride frequency has been successfully generated on accelerometers and/or gyroscopes attached to both lumbar and lower limb attachment points[51] research has shown that sprinting analysis can lead to diminished acceleration patterns with lumbar attachment[17] and so lower limb and tibia attachment are recommended. Whilst gyroscopes alone were also utilised to derive stride frequency, they were validated against a subjective comparison method (2D video analysis) and have been found to provide greater complications than accelerometers (drift etc.) and so accelerometers are recommended in terms of the sensor utilised. For temporal parameters a common technique utilised which has also been validated at different speeds and with various subjects (i.e. paralympian) is identifying foot contact through examination of the acceleration curves. Again this would be recommended with tibial or lower limb attachment for distinct patterns and also to minimise time lag between accelerometer data and actual foot contact. While gyroscopes have also previously been utilised it was found that those that validated against 3D motion capture generated less accurate parameter output as speed increased. This would again lead to the recommendation of accelerometer utilisation for temporal parameter collection. For gait pattern research visual inspection of the acceleration curve (and the key gait markers associated with it) generated via accelerometers has been validated against both in-shoe sensors and 2D motion capture. Research here has also shown that lower limb (ankle) attachment has provided greater accuracy in providing gait pattern analysis than hip placement[49] which is consistent in previous research. However it is suggested that if lower limb attachment is not possible, perhaps due to limitation of sensor quantity availability, but gait information is still desired that running speed be maintained between 2.8-5.3 m/s. This speed, along with lumbar sensor attachment, has been previously validated in gait pattern analysis[47] whilst higher speeds (5.7-10.8 m/s) have been found to dampen gait pattern acceleration curves[17]. For stride length limited information in the derivation of results has been outlined with only the advanced pedestrian dead reckoning method utilised by Bichler et al.[18] and dividing treadmill speed by stride frequency[35, 36] being stated in the literature. Of these methods Bichler et al.[18] is the only author to have provided validation and so this method may be the preferred. Again though this parameter, stride length, was most sensitive to error at higher speeds and so perhaps following similar guidelines and speeds suggested for the derivation of gait pattern (previously mentioned) should be followed to control this risk of error. Accelerometers and/or gyroscopes have also been utilised in deriving other lower body parameters such as foot strike type and heel lift and upper body parameters (arm movement, trunk forward lean etc.) however due to limited research on these parameters it is difficult to make future guidelines as to the most accurate methodology to be employed when these are of interest. However by utilising general guidelines as to the placement[40] and weight[42] of these sensors and by following recommendations on the derivation of similar parameters this may lead to greater accuracy in data collection.

4.2 General recommendations

Overall, research utilising gyroscopes (individually) in the analysis of running gait has proven to be limited. Whilst ten of the articles within this review utilised IMU's some did not utilise the gyroscope capabilities of these units and most focused on the acceleration data generated. There therefore remains a question whether future research should focus on the use of gyroscopes. From the information collected within this systematic review gyroscopes have demonstrated greater limitations (i.e. drift) than accelerometers, while accelerometers have been successfully utilised to ascertain valid data gyroscopes are primarily utilised for angular velocity[12], whilst also being easier to work with. Finally, to our knowledge, while previous studies have regularly investigated short distance running trials and sprints, no authors have addressed longitudinal running gait analysis, in terms of over an extended period of time and over longer distances, using accelerometers/and or gyroscopes. This is an important area which should be addressed as information gathered over an extended period could divulge important data related to overuse injury.

5. Conclusion

Based on the evidence provided we are able to support the use of accelerometer and/or gyroscopes in the analysis of running gait, as it is clear they have been utilised, and validated, in the use of deriving research and coach orientated kinematic parameters. Within this however it is important to point out that many different methodologies have been utilised by previous researchers in areas such as attachment site, type of sensor and different calculation methods to generate kinematic data. As to which methodology is correct it is important for future scientists and coaches to clearly identify what parameters they wish to investigate and to then let this lead the methodology. The importance of accelerometers and/or gyroscopes in combating increasing levels of RRI is valid as by accurate generation of kinematic data they may provide a wealth of information on ever-changing running patterns in an unobtrusive and natural environment.

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