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Title;

Profiling movement and gait quality characteristics in early-years children (3-5y) - *Original Research Article*

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Abstract

There is a dearth of suitable metrics capable of objectively quantifying motor competence. Further, objective movement quality characteristics during free-play have not been investigated in early years' children. The aims of this study were to characterise children's free-play physical activity and to investigate how gait quality characteristics cluster with free-play in children (3-5y). Sixty-one children (39 boys, 4.3±0.7y, 1.04±0.05m, 17.8±3.2kg) completed the movement assessment battery for children and took part in free-play whilst wearing an ankle- and hip-mounted accelerometer. Characteristics of movement quality were profiled using a clustering algorithm. Spearman's rho and the Mann-Whitney U tests were used to assess relationships between movement quality characteristics and motor competence classification differences in integrated acceleration and spectral purity, respectively. Significant differences were found between motor competency classifications for spectral purity and integrated acceleration ($P<0.001$). Spectral purity was hierarchically clustered with motor competence and integrated acceleration. Significant positive correlations were found between spectral purity, integrated acceleration and motor competence ($P<0.001$). This is the first study to report spectral purity in early years' children and our results suggest that the underlying frequency component of movement is clustered with motor competence.

Key words: Clustergram; Accelerometer; Spectral purity; Motor competence;

Running head: Early years' children movement characteristics

Introduction

Global physical activity guidelines recommend that early years' children (3-5 years) engage in at least 180 minutes of physical activity every day (Department of Health, 2011; Tremblay et al., 2011). Demographic, biological, sociocultural, and motor competence can all impact upon physical activity levels (Barnett et al., 2016; Bingham et al., 2016; Hesketh et al., 2014; Lubans et al., 2010). Specifically, Stodden et al. (2008) highlighted inter-relations between motor competence, perceived motor competence, cardiorespiratory fitness and physical activity levels. Further, recent prospective studies have established that development of motor competence has numerous tangible health and developmental benefits. For example, higher levels of motor competence are shown to positively predict cardiorespiratory fitness (Vlahov et al., 2014), improved academic performance (Jaakkola et al., 2015), and are protective against overweight and obesity (Rodrigues et al., 2015). Concerningly, studies have reported low levels of competence among primary school aged children (Bryant et al., 2013; LeGear et al., 2012). These findings highlight the need to examine motor competence during early years (3-5 years), which is considered a critical phase for fundamental movement skill development (Gallahue & Donnelly, 2003). During this period, neuromuscular maturation and rapid cognitive development affect motor skill acquisition and development (Malina et al., 2004). Motor development during the early years is considered a facilitator for lifelong physically active lifestyles, and children's perceptions of their competency is asserted to influence this development (LeGear et al., 2012). For example, older children who perceive themselves as having poor motor competence may fall into a negative spiral of disengagement, further limiting motor development, physical activity and cardiorespiratory fitness (Stodden et al., 2008). Several studies have documented low levels of motor competence among early years' children (Barnett et al., 2014; Cliff et al., 2009; Goodway et al., 2010; Hardy et al., 2010; Robinson, 2011; Ulrich, 2000). Motor competence in the early years is traditionally assessed using observation tools in a controlled setting, such as the movement assessment battery for children (MABC2 (Henderson et al., 2007)) or the test of gross motor development (TGMD (Ulrich, 1985, 2000)). To our knowledge there have been no objective measurements of motor competence and movement quality during habitual child activity (Clark, Barnes, Stratton, et al., 2016), and this dearth of literature has resulted in limited insight into children's motor development. We postulate that objective measures and novel analytics will provide insight into the quality and quantity of movement in parallel (Clark, Barnes, Stratton, et al., 2016).

Developments in the field of objectively measured physical activity are moving with expediency (Clark, Barnes, Stratton, et al., 2016). For example, accelerometers can be used to characterise gait patterns and determine safety, control, balance, variability and rhythmicity during ambulation (Aziz et al., 2014; Aziz & Robinovitch, 2011; Bellanca et al., 2013; Brach et al., 2011; Kangas et al., 2015). In addition, movement quality characteristics are retrievable using Fourier analysis and the harmonic content of an accelerometer signal, by analysing the symmetry within a movement, exploiting the periodicity of the signal (Gage, 1964; Smidt et al., 1971). The resulting spectral purity and integrated accelerations of each movement can be analyzed to assess, and profile, movement quality in children (Bellanca et al., 2013; Clark, Barnes, Holton, et al., 2016b; Clark et al., 2015). This type of analysis is highly suggestive of the fundamental neural control of movement (Stergiou & Decker, 2011) and shown to be representative of movement quality in standardised settings (Clark, Barnes, Holton, et al., 2016b). However, this has not been investigated in early years' children.

Statistically, the use of traditional measures to study physical activity in humans assumes that variations are random and independent of past and future repetitions (Lomax, 2007), contrastingly however, it has been shown that such variations are distinguishable from noise and warrant further investigation (Delignieres & Torre, 2009; Dingwell & Cusumano, 2000; Dingwell & Kang, 2007; Stergiou et al., 2004; Stergiou & Decker, 2011). Moreover, frequency spectrum characteristics derived from an accelerometer signal are significantly related to movement quality, cardiorespiratory fitness, running strategy and body mass index in primary school children (Barnes et al., 2016; Clark, Barnes, Holton, et al., 2016b).

Although some recent work has examined the relationship between motor skills and physical activity, in a standardised setting (incorporating accelerometry) (Laukkanen, Finni, et al., 2013; Laukkanen, Pesola, et al., 2013), there has been no attempt in the literature to use clustering algorithms to profile and compare derivatives of a raw acceleration trace (spectral purity, integrated acceleration) during free-play in early years' children. There is clearly potential to derive more information from the signal output of accelerometers (Clark, Barnes, Stratton, et al., 2016). Therefore, the aims of this study were two-fold; to characterise children's free-play physical activity and investigate how movement quality characteristics of gait cluster in children (3-5y).

2.0 Method

2.1. Participants and Settings

Sixty-one children (39 boys, 4.3±0.7y, 1.04±0.05m, 17.8±3.2kg, body mass index; 16.2±1.9 $kg{\cdot}m^2$) volunteered to take part in this study from two primary schools in Northern England, United Kingdom (U.K) (77% South Asian, 12% White British, 11% Other/Mixed). Prior to research commencing, informed parental consent and child assent was attained. This research was conducted in agreement with the guidelines and policies of the institutional ethics committee.

2.2. Instruments and Procedures

Children took part in a free-play period, which for the purpose of this study is synonymous with recess, (104 ± 12 minutes per day) while their physical activity was recorded using a custom-built Micro Electro-Mechanical System (MEMS) based device, which incorporated a tri-axial accelerometer with a +/- 16g dynamic range, 3.9mg point resolution and a 13-bit resolution (with a z-axis amplitude coefficient of variation of 0.004 at 40 Hz (Clark, Barnes, Holton, et al., 2016c);ADXL345 sensor, Analog Devices). The MEMS device was housed in a small plastic case and affixed via a Velcro strap to the lateral malleolar prominence of the fibula of the right leg and set to record at 40 Hz (Barnes et al., 2016; Clark, Barnes, Holton, et al., 2016b). Mannini et al. (2013) highlighted that for movement quality characteristics related to ambulation, an ankle-mounted monitor may be most suitable, and Barnes et al. (2016) systematically demonstrated that ankle affixed accelerometers can be used to accurately compute leg lift angle. Data were stored locally on the device and there were no incidences of data loss. Moderate-to-vigorous physical activity was also measured using an additional ActiGraph GT3X+ device (ActiGraph, Pensacola, FL, USA) mounted on the right hip and set to record at 100 Hz, in accordance with manufacturer guidelines. All children also completed the movement assessment battery for children, second edition, using standardised procedures (MABC2; as detailed in: Henderson et al. (2007)).

2.2.1. Anthropometrics

Stature (measured to the nearest 0.01m) and body mass (to the nearest 0.1kg) were measured using standard procedures using a stadiometer and digital scales (SECA, Hamburg, Germany), respectively (Lohmann et al., 1988). Skinfold measurements of the left triceps and subscapular were made by trained researchers using calibrated skinfold callipers (Harpenden, Baty International, U.K.), waist circumference was measured at the level of the naval and measurements were subsequently used to estimate body fat percentage (Eisenmann et al., 2004; Slaughter et al., 1988). Reliability metrics indicated good intra- and inter-observer technical error for measurements (Collings et al., 2017). Further, children were classified based on body-mass index percentiles as either; underweight (≤5th percentile), normal weight (5th to 85th

percentile), overweight (>85th to <95th percentile) or obese (≥ 95th percentile) (Cole & Lobstein, 2012).

2.3. Data Analysis

Raw acceleration data from the MEMS device were uploaded into MatLab (MATLAB version R2016a), where integrated acceleration and spectral purity were derived (Barnes et al., 2016; Clark, Barnes, Holton, et al., 2016b). The characteristics used for analysis were derived from acceleration in the axis along the lower leg towards the origin of motion, termed the radial axis. The integrated acceleration was determined using an integration of the rectified raw acceleration signal (van Hees et al., 2010).

Acceleration data were converted from the time into the frequency domain. In order to convert the data into the frequency domain the Fast Fourier transform was applied to the data. The Fast Fourier Transform computes the discrete Fourier transform (DFT) of a sequence.

Let x_0,…,x_(N-1) be a sequence of N complex numbers. The Fast Fourier transform computes the Discrete Fourier transform

$$X_k = \sum_{n=0}^{N-1} x_n . e^{-i2\pi kn/N} , k \in Z$$

Equation 1. Fast Fourier Transform

Where, N = number of time samples, n = current sample under consideration (0 .. N-1), x_n = value of the signal at time n, k = current frequency under consideration (0 Hertz up to N-1 Hertz), X_k = amount of frequency k in the signal (amplitude and phase, a complex number), n/N is the percent of the time gone through, 2 * pi (π) * k is the speed in radians·sec^{-1}, e^-ix is the backwards-moving circular path.

In order to determine the quality of a child's movement - 'Spectral purity' was calculated from the cumulative distribution function (CDF) of the frequency spectrum. The CDF plot is used to generate a value for spectral purity. The empirical CDF *F(x)* is defined as the proportion of X values less than or equal to some value *x*. In this case, it is the number of values less than or equal to some frequency in a spectrum being considered. A measure for spectral purity is therefore considered to be the frequency at which the midway point of the CDF (0.5) occurs. As a result, spectra that is 'clean', i.e. consisting of a tall narrow peak at the fundamental frequency and only low amount of noise and small harmonics will have a different value to spectra where there is lots of noise, a shorter wider peak, and higher peaks at the harmonics.

Spectral purity measures how tightly the frequency components of the raw accelerations are distributed using fundamental frequency to harmonics and the frequency spectrum analysis is directly related to the ambulation of a participant (Barnes et al., 2016; Clark, Barnes, Holton, et al., 2016b). A participant could have high spectral purity and low overall activity, which indicates that cyclical, high periodicity movement has occurred. However, in combination with low integrated acceleration this equates to the participant remaining static, for example, sat down in one location for prolonged periods.

ActiGraph acceleration data were analyzed using a commercially available analysis tool (KineSoft version 3.3.67, KineSoft; www.kinesoft.org). Non-wear periods were defined as any sequence of >20 consecutive minutes of zero activity counts (Tudor-Locke et al., 2015). Sedentary behaviour was defined as <100 counts per minute, while 100, 2296 and 4012 counts per minute were thresholds to define light, moderate and vigorous physical activity, respectively (Evenson et al., 2008; Trost et al., 2011). Mean counts per minute during valid wear time and percentage of total time spent in moderate-to-vigorous physical activity (MVPA) were used to define physical activity.

The MABC2 was scored by a trained, experienced assessor and scores were described in a traffic light classification system including a red zone (1: <5th percentile indicating significant movement difficulty), amber zone (2: between the 5th and 15th percentiles indicating at risk of movement difficulty), and green zone (3: >15th percentile indicating no movement difficulty detected), following standard procedures (Henderson et al., 2007).

2.3.1 Cluster analysis

Hierarchical clustering is an analytic procedure that reduces multi-factorial data into smaller subsets, where numerous and complex characteristics of movement and lifestyle in adults and children (9-11y) can be reliably analysed (Clark, Barnes, Holton, et al., 2016b; Schonlau, 2002; Tonkin et al., 2012). Clustering yields groupings that are based on the similarity of whole cases, as opposed to the individual variables that comprise those cases (Leonard & Droege, 2008).

Cluster analysis has been used to profile and classify systems or taxonomies (Leonard & Droege, 2008; Sokal & Rohlf, 1962), and whilst it has consistently been applied in other disciplines, such as nanotechnology and cell biology (Armstrong et al., 1996; Johnson, 1997; Schweitzer & Renehan, 1997; Semmar et al., 2005; Winterstein et al., 2004), it has only recently been used successfully to investigate human movement characteristics (Clark, Barnes, Holton, et al., 2016b).

The derived characteristics (integrated acceleration, spectral purity, overall activity counts, MVPA percentage, BMI percentile, MABC2 classification, body fat percentage) were normalised so that they could be compared and input into an in-built clustering algorithm (MATLAB version R2016a). This algorithm goes through multiple iterative processes in order to cluster the data along the columns of the dataset. The similarity or dissimilarity between metrics was determined by calculating the pairwise Euclidean distances between the values of the different metrics.

$$d_{2st} = (x_s - x_t)(x_s - x_t)'$$

Equation 2. Euclidean distance

Where, d is the Euclidean distance; x_s and x_t represent the data values being compared.

Once the distances between the characteristics (integrated acceleration, spectral purity, overall activity counts, MVPA percentage, BMI percentile, MABC2 classification, body fat percentage) for each child were derived, a linkage function was applied, to determine the proximity of the metrics to each other. These were paired into binary clusters, which were subsequently grouped into larger clusters until a hierarchical tree was formed. The resulting clustergram was displayed in terms of a heat map and dendrogram. The height of the link at which two observations on the dendrogram were joined was analysed using cophenetic distance (Equation 3), to demonstrate the similarity between two clusters (Saracli et al., 2013; Schonlau, 2002; Sokal & Rohlf, 1962). The values for the dendrogram linkages were subsequently normalised. The cophenetic distance ratio for the overall clustergram was also measured to demonstrate how successfully the dendrogram preserved the pairwise distances between the original unmodeled data points (where 1 is maximum).

$$c = \frac{\sum_{i<j}(Y_{ij} - y)(Z_{ij} - z)}{\sqrt{\sum_{i<j}(Y_{ij} - y)^2 \sum_{i<j}(Z_{ij} - z)^2}}$$

Equation 3. Cophenetic distance equation

Where Y_{ij} is the distance between objects i and j in Y. Z_{ij} is the cophenetic distance between objects i and j, from Z. y and z are the average of Y and Z, respectively.

A Shapiro-Wilk test determined that data were not normally distributed ($P<0.001$) and therefore non-parametric inferential methods were used for analysis. Descriptive data were presented as mean, median and upper and lower quartiles (Clark, Barnes, Holton, et al., 2016b). The Kruskall-Wallis test was used to determine differences between motor competence traffic light groups and post-hoc Mann-Whitney U tests, with continuity correction and tie adjustment (Gibbons & Chakraborti, 2011), to determine specific differences between groups. Spearman's rho was used to calculate correlation coefficients between each characteristic. All inferential statistics were performed using MatLab (MATLAB version R2016a). Statistical significance was accepted at $P\leq0.05$.

3.0 Results

Significant differences were found between MABC2 classification groups for spectral purity and integrated acceleration. Post-hoc testing found significant differences between green, amber and red MABC2 classifications for spectral purity and integrated acceleration ($P<0.001$). Descriptive data for movement and physical activity characteristics are detailed in Table 1. Significant ($P\leq0.05$) relationships were found between MABC2 classification and percentage of time spent in moderate-to-vigorous physical activity (r=0.29), integrated acceleration (r=0.66) and spectral purity (r=0.7). Significant correlations were also found between spectral purity and integrated acceleration (r=0.57), and body fat percentage and BMI percentile (r=0.75). Figure 1 illustrates that integrated acceleration and spectral purity (cophenetic distance (CD): 0.19), integrated acceleration and MABC2 classification (CD: 0.19), spectral purity and MABC2 classification (CD: 0.06), were clustered together (Figure 1), with a cophenetic distance ratio for the overall clustergram of 0.95.

Discussion

The aims of this study were to characterise children's free-play physical activity, and investigate how movement quality characteristics of gait cluster in children (3-5y).

Clustergram overview

In order for a clustergram to be considered statistically accurate, a cophenetic distance ratio of 0.75 is required (Bradley & Stentiford, 2003). The clustergram in this study had a cophenetic distance ratio of 0.95, indicating confidence in the veracity of clusters identified. The clustering algorithm hierarchically linked each characteristic (integrated acceleration, spectral purity, overall activity counts, MVPA percentage, BMI percentile, MABC2 classification, body fat percentage), accordingly. The proximity of two or more characteristics within the clustergram indicated how closely the movement quality characteristics were linked to each other

(Schonlau, 2002; Sokal & Rohlf, 1962), for example, MABC2 classification and spectral purity: 0.06, integrated acceleration and spectral purity: 0.19. The cophenetic distance ratio reported in the present study indicates that movement characteristics were successfully, and reliably, clustered. Hierarchically clustering movement characteristics has previously been shown to be successful in pre-adolescent children and close cophenetic distances between spectral purity and aerobic performance were highlighted (Clark, Barnes, Holton, et al., 2016b). However, this is the first study to utilise and report the hierarchical clustering of movement characteristics in early-years children.

Integrated acceleration, spectral purity and motor competence

The frequency and harmonic content of movement is reflective of movement characteristics such as gait pattern and overall physical activity, in addition to cardiorespiratory fitness (Clark, Barnes, Holton, Mackintosh, et al., 2016; Clark, Barnes, Holton, et al., 2016b). In this study, spectral purity and motor competence (MABC2 classification) were more closely cophenetically linked (0.06) than integrated acceleration (0.19), which was previously unreported. Furthermore, traditional correlation analyses found spectral purity (r=0.7) and integrated acceleration (0.66) were significantly correlated with motor competence. These findings suggest that spectral purity and integrated acceleration may be movement quality indicators in early years' children, congruent with previous findings where spectral purity was demonstrated to be indicative of fundamental aspects of movement in pre-adolescent children (9-11y) (Clark, Barnes, Holton, et al., 2016b). Furthermore, in a population of geriatric and Parkinsonian sufferers', accelerometer signals in the frequency domain reveal deteriorating gait characteristics and predict fall potential, respectively (Howcroft et al., 2013; Sejdic et al., 2014). To the authors' knowledge, the present study is the first to demonstrate that spectral purity and motor competence are related in early years' children (Figure 1).

Integrated acceleration, a proxy measure for overall physical activity (Clark, Barnes, Holton, et al., 2016b; van Hees et al., 2012), was positively related to motor competence in the present study and this is supported widely in the literature (Barnett et al., 2016; Barnett et al., 2014, 2015; Robinson et al., 2015). Although some studies have relied upon self-report proxies of physical activity (Erwin & Castelli, 2008; Graf et al., 2004), a recent review found a positive relationship between motor competence and health-related benefits (Barnett et al., 2016). Further, Holfelder and Schott (2014) and Lubans et al. (2010) also reported positive associations in respective systematic reviews, and Cohen et al. (2014) demonstrated that overall physical activity was positively correlated with locomotor and object control competency. Congruent with previous work (Cohen et al., 2014; Holfelder & Schott, 2014; Lubans et al., 2010), integrated acceleration was significantly different by MABC2 classification ($P<0.001$). However, spectral purity was also found to significantly different by MABC2 classification ($P<0.001$). In preceding work, empirical evidence suggested that spectral purity was a viable proxy measure of the fundamental aspects of movement and that it clustered with motor competence (see: Clark, Barnes, Holton, et al. (2016b) and Barnes et al. (2016)). Further, given that the present study has demonstrated that spectral purity is clustered with motor competence and significantly different between motor competency classification, suggests underlying frequency components of movement should be further investigated for the measurement of movement quality in children (Clark, Barnes, Holton, et al., 2016b). Moreover, whilst it has been demonstrated that a proxy for overall physical activity was positively correlated with motor competence (Cohen et al., 2014; Holfelder & Schott, 2014; Lubans et al., 2010), spectral purity ($r=0.7$) was found to have a stronger relationship to motor competence than overall activity (0.66) in the present study, thereby highlighting the need for future research to examine and further establish this relationship.

Anthropometrics. age and actigraphy

Congruent with previous research, the present study found that BMI and body fat percentage were closely cophenetically clustered and significantly positively correlated (Cui et al., 2013; Lindsay et al., 2001). Whilst previous research has highlighted that motor competence and physical activity are inversely correlated with weight status in children (Cairney et al., 2005; Lopes et al., 2011; Lopes et al., 2012; Rivilis et al., 2011), we found that anthropometric characteristics were not clustered, nor correlated to any other measure (Figure 1). This is reflected in the literature, as Ekelund et al. (2012) and Vorwerg et al. (2013) reported no differences in physical activity levels in early years' children according to BMI and that physical activity levels did not significantly differ between overweight/obese children and normal-weight peers, respectively. Further, Williams et al. (2008) reported that there was no significant association between BMI and motor skill performance concluding that whilst weight status of early years' children was considerably influenced by socioeconomic status, physical activity levels were not, potentially due to the highly transitory and frequent movement during nursery/preschool.

Traditional hip-mounted accelerometer data did not cluster with any movement characteristic, whilst concurrent ankle-mounted raw accelerometry yielded significant results. One explanation is that traditional hip-mounted accelerometers have inadequate band-pass filtering, where high frequency movement and noise information can escape the filter adding unexplained variation in activity counts (Brond & Arvidson, 2015). Further, Wundersitz et al. (2015) identified that filters with at least an 8 or 10 Hz cut-off frequency were most suitable to process accelerations in ambulatory tasks, and thus adopted in the present study, whereas the actigraphy device utilised filters out frequencies higher than 2.5 Hz (Brond & Arvidson, 2015; Wundersitz et al., 2015). This finding highlights the insensitivity of traditional, hip-worn actigraphy units to measure contextualised physical activity. Physical activity is a multi-directional, complex construct and summative activity counts are a measure of centrality that are missing vital information (Bussmann & van den Berg-Emons, 2013; Stergiou & Decker, 2011). This study highlighted that integrated acceleration and spectral purity are hierarchically clustered and significantly correlated with motor competency, whereas traditional, hip mounted, physical activity measures do not.

Limitations

The clustering algorithm utilised within this study was structured using hierarchical methods, thereby pairing characteristics according to proximity. This means inverse relationships may be difficult to ascertain. However, this can be mitigated with careful interpretation of the clustergram, in addition to incorporating other correlation analyses (i.e. Spearman's rho). Although this study employed novel signal analytics of accelerometer data, it only assessed spectral purity and integrated acceleration, and therefore further analytics could be employed and should be the focus of future research.

Conclusion

The aims of this study were to characterise children's free-play physical activity and to investigate how movement characteristics of gait cluster in children (3-5y). Overall, integrated acceleration and spectral purity were significantly different between motor competence classifications. Further, that overall physical activity and spectral purity cluster during uncontrolled free-play physical activity, whilst spectral purity was more closely linked to motor competence than integrated acceleration. Anthropometric and actigraphy characteristics were not correlated to, or clustered meaningfully with, any other measure.

This study has built upon previous research (Barnes et al., 2016; Clark, Barnes, Holton, et al., 2016a, 2016b) highlighting cophenetic clustering of spectral purity with integrated physical activity and motor competence. The analysis of frequency and harmonic content of movement and overall physical activity concomitantly is demonstrably sensitive and informative and may be able to distinguish between motor competency in early childhood. We recommend that future research seeks to better quantify and qualify physical activity in contextualised settings to enhance our understanding of specific movement and gait patterns. Furthermore, the link between spectral purity and motor competence highlighted in this study necessitates detailed further investigation.

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Conflict of Interest

The authors declare that there are no conflict of interests or sources of financial assistance regarding the publication of this paper and that the results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

References

Armstrong, R. A., Wood, L., Myers, D., & Smith, C. U. (1996). The use of multivariate methods in the identification of subtypes of Alzheimer's disease: a comparison of principal components and cluster analysis. *Dementia, 7*(4), 215-220. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/8835886

Aziz, O., Park, E. J., Mori, G., & Robinovitch, S. N. (2014). Distinguishing the causes of falls in humans using an array of wearable tri-axial accelerometers. *Gait Posture, 39*(1), 506-512. doi:10.1016/j.gaitpost.2013.08.034

Aziz, O., & Robinovitch, S. N. (2011). An analysis of the accuracy of wearable sensors for classifying the causes of falls in humans. *IEEE Trans Neural Syst Rehabil Eng, 19*(6), 670-676. doi:10.1109/TNSRE.2011.2162250

Barnes, C. M., Clark, C. C., Holton, M. D., Stratton, G., & Summers, H. D. (2016). Quantitative Time-Profiling of Children's Activity and Motion. *Med Sci Sports Exerc*. doi:10.1249/MSS.0000000000001085

Barnett, L., Stodden, D. F., Cohen, K. E., Smith, J. J., Lubans, D. R., Lenoir, M., . . . Morgan, P. J. (2016). Fundamental Movement Skills: An Important Focus. *Journal of Teaching in Physical Education, Advance Online Publication*. doi:http://dx.doi.org/10.1123/jtpe.2014-0209

Barnett, L. M., Ridgers, N. D., & Salmon, J. (2014). Associations between young children's perceived and actual ball skill competence and physical activity. *Journal of Science and Medicine in Sport*(0). doi:http://dx.doi.org/10.1016/j.jsams.2014.03.001

Barnett, L. M., Ridgers, N. D., & Salmon, J. (2015). Associations between young children's perceived and actual ball skill competence and physical activity. *J Sci Med Sport, 18*(2), 167-171. doi:10.1016/j.jsams.2014.03.001

Bellanca, J. L., Lowry, K. A., Vanswearingen, J. M., Brach, J. S., & Redfern, M. S. (2013). Harmonic ratios: a quantification of step to step symmetry. *J Biomech, 46*(4), 828-831. doi:10.1016/j.jbiomech.2012.12.008

Bingham, D. D., Costa, S., Hinkley, T., Shire, K. A., Clemes, S. A., & Barber, S. E. (2016). Physical Activity During the Early Years: A Systematic Review of Correlates and Determinants. *Am J Prev Med, 51*(3), 384-402. doi:10.1016/j.amepre.2016.04.022

Brach, J. S., McGurl, D., Wert, D., Vanswearingen, J. M., Perera, S., Cham, R., & Studenski, S. (2011). Validation of a measure of smoothness of walking. *J Gerontol A Biol Sci Med Sci, 66*(1), 136-141. doi:10.1093/gerona/glq170

Bradley, A., & Stentiford, F. A. (2003). Visual attention for region of interest coding in JPEG 2000. *J. Vis. Commun. Image R., 14*, 232-250.

Brond, J. C., & Arvidson, D. (2015). *Sampling frequency affects ActiGraph activity counts.* Paper presented at the ICAMPAM, Limerick, Ireland.

Bryant, E. S., Duncan, M. J., & Birch, S. L. (2013). Fundamental movement skills and weight status in British primary school children. *Eur J Sport Sci*, 1-7. doi:10.1080/17461391.2013.870232

Bussmann, J. B., & van den Berg-Emons, R. J. (2013). To total amount of activity..... and beyond: perspectives on measuring physical behavior. *Front Psychol, 4*, 463. doi:10.3389/fpsyg.2013.00463

Cairney, J., Hay, J. A., Faught, B. E., & Hawes, R. (2005). Developmental coordination disorder and overweight and obesity in children aged 9-14 y. *Int J Obes (Lond), 29*(4), 369-372. doi:10.1038/sj.ijo.0802893

Clark, C. C., Barnes, C. M., Stratton, G., McNarry, M. A., Mackintosh, K. A., & Summers, H. D. (2016). A Review of Emerging Analytical Techniques for Objective Physical Activity Measurement in Humans. *Sports Med*. doi:10.1007/s40279-016-0585-y

Clark, C. C. T., Barnes, C. M., Holton, M. D., Mackintosh, K. A., Summers, H. D., & Stratton, G. (2016). *Profiling movement quality characteristics according to body-mass index in children.* Paper presented at the 21st Annual Congress of the European College of Sport Science, Vienna, Austria.

Clark, C. C. T., Barnes, C. M., Holton, M. D., Summers, H. D., & Stratton, G. (2016a). A kinematic analysis of fundamental movement skills. *Sport Science Review, 25*(3-4), 261-275.

Clark, C. C. T., Barnes, C. M., Holton, M. D., Summers, H. D., & Stratton, G. (2016b). Profiling movement quality and gait characteristics according to body-mass index in children (9–11 y). *Hum Mov Sci, 49*, 291-300. doi:http://dx.doi.org/10.1016/j.humov.2016.08.003

Clark, C. C. T., Barnes, C. M., Holton, M. D., Summers, H. D., & Stratton, G. (2016c). SlamTracker Accuracy under Static and Controlled Movement Conditions. *Sport Science Review, 25*(5-6), 321-344.

Clark, C. C. T., Barnes, C. M., Mackintosh, K. A., Summers, H., & Stratton, G. (2015). *Quantitative, multiscale profiling of Motion and Activity in Children.* Paper presented at the 20th Annual Conference of the European College of Sport Science, Malmo, Sweden.

Cliff, D. P., Okely, A. D., Smith, L. M., & McKeen, K. (2009). Relationships between fundamental movement skills and objectively measured physical activity in preschool children. *Pediatr Exerc Sci, 21*(4), 436-449. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/20128363

Cohen, K. E., Morgan, P. J., Plotnikoff, R. C., Callister, R., & Lubans, D. R. (2014). Fundamental movement skills and physical activity among children living in low-income communities: a cross-sectional study. *Int J Behav Nutr Phys Act, 11*(1), 49. doi:10.1186/1479-5868-11-49

Cole, T. J., & Lobstein, T. (2012). Extended international (IOTF) body mass index cut-offs for thinness, overweight and obesity. *Pediatr Obes, 7*(4), 284-294. doi:10.1111/j.2047-6310.2012.00064.x

Collings, P. J., Brage, S., Bingham, D. D., Costa, S., West, J., McEachan, R. R., . . . Barber, S. E. (2017). Physical Activity, Sedentary Time, and Fatness in a Biethnic Sample of Young Children. *Med Sci Sports Exerc*. doi:10.1249/MSS.0000000000001180

Cui, Z., Truesdale, K. P., Cai, J., Koontz, M. B., & Stevens, J. (2013). Anthropometric indices as measures of body fat assessed by DXA in relation to cardiovascular risk factors in children and adolescents: NHANES 1999-2004. *Int J Body Compos Res, 11*(3-4), 85-96. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/26405434

Delignieres, D., & Torre, K. (2009). Fractal dynamics of human gait: a reassessment of the 1996 data of Hausdorff et al. *J Appl Physiol (1985), 106*(4), 1272-1279. doi:10.1152/japplphysiol.90757.2008

Dingwell, J. B., & Cusumano, J. P. (2000). Nonlinear time series analysis of normal and pathological human walking. *Chaos, 10*(4), 848-863. doi:10.1063/1.1324008

Dingwell, J. B., & Kang, H. G. (2007). Differences between local and orbital dynamic stability during human walking. *J Biomech Eng, 129*(4), 586-593. doi:10.1115/1.2746383

Eisenmann, J. C., Heelan, K. A., & Welk, G. J. (2004). Assessing body composition among 3- to 8-year-old children: anthropometry, BIA, and DXA. *Obes Res, 12*(10), 1633-1640. doi:10.1038/oby.2004.203

Ekelund, U., Luan, J., Sherar, L. B., Esliger, D. W., Griew, P., Cooper, A., & International Children's Accelerometry Database, C. (2012). Moderate to vigorous physical activity and sedentary time and cardiometabolic risk factors in children and adolescents. *JAMA, 307*(7), 704-712. doi:10.1001/jama.2012.156

Erwin, H. E., & Castelli, D. M. (2008). National physical education standards: a summary of student performance and its correlates. *Res Q Exerc Sport, 79*(4), 495-505. doi:10.1080/02701367.2008.10599516

Evenson, K. R., Catellier, D. J., Gill, K., Ondrak, K. S., & McMurray, R. G. (2008). Calibration of two objective measures of physical activity for children. *J Sports Sci, 26*(14), 1557-1565. doi:10.1080/02640410802334196

Gage, H. (1964). Accelerographic analysis of human gait. *The American Society of Mechanical Engineers, 64-WA/HUF-8*, 1-12.

Gallahue, D. L., & Donnelly, F. C. (2003). *Developmental physical education for all children* (4th ed.). Champaign, IL: Human Kinetics.

Gibbons, J. D., & Chakraborti, S. (2011). *Nonparametric statisical inference* (5th ed.). Boca Raton, FL: Chapman & Hall/CRC press, Taylor & Francis group.

Goodway, J. D., Robinson, L. E., & Crowe, H. (2010). Gender Differences in Fundamental Motor Skill Development in Disadvantaged Preschoolers From Two Geographical Regions. *Res Q Exerc Sport, 81*(1), 17-24. doi:10.1080/02701367.2010.10599624

Graf, C., Koch, B., Kretschmann-Kandel, E., Falkowski, G., Christ, H., Coburger, S., . . . Dordel, S. (2004). Correlation between BMI, leisure habits and motor abilities in childhood (CHILT-project). *Int J Obes Relat Metab Disord, 28*(1), 22-26. doi:10.1038/sj.ijo.0802428

Hardy, L. L., King, L., Farrell, L., Macniven, R., & Howlett, S. (2010). Fundamental movement skills among Australian preschool children. *Journal of Science and Medicine in Sport, 13*(5), 503-508. doi:10.1016/j.jsams.2009.05.010

Health, D. o. (2011). *Start Active, Stay Active: A report on physical activity from the four home countries' Chief Medical Officers*. London, UK.

Henderson, S., Sugden, D., & Barnett, A. (2007). *Movement assessment battery for children-2 second edition [Movement ABC-2]*. London, UK: The Psychological Corporation.

Hesketh, K. R., McMinn, A. M., Ekelund, U., Sharp, S. J., Collings, P. J., Harvey, N. C., . . . van Sluijs, E. M. (2014). Objectively measured physical activity in four-year-old British children: a cross-sectional analysis of activity patterns segmented across the day. *Int J Behav Nutr Phys Act, 11*(1), 1. doi:10.1186/1479-5868-11-1

Holfelder, B., & Schott, N. (2014). Relationship of fundamental movement skills and physical activity in children and adolescents: A systematic review. *Psychol Sport Exerc, 15*(4), 382-391. doi:10.1016/j.psychsport.2014.03.005

Howcroft, J., Kofman, J., & Lemaire, E. D. (2013). Review of fall risk assessment in geriatric populations using inertial sensors. *J Neuroeng Rehabil, 10*(1), 91. doi:10.1186/1743-0003-10-91

Jaakkola, T., Hillman, C., Kalaja, S., & Liukkonen, J. (2015). The associations among fundamental movement skills, self-reported physical activity and academic performance during junior high school in Finland. *J Sports Sci*, 1-11. doi:10.1080/02640414.2015.1004640

Johnson, M. (1997). Using cluster analysis to develop a healing typology in vascular ulcers. *J Vasc Nurs, 15*(2), 45-49. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/9238941

Kangas, M., Korpelainen, R., Vikman, I., Nyberg, L., & Jamsa, T. (2015). Sensitivity and false alarm rate of a fall sensor in long-term fall detection in the elderly. *Gerontology, 61*(1), 61-68. doi:10.1159/000362720

Laukkanen, A., Finni, T., Pesola, A., & Saakslahti, A. (2013). Reipas liikunta takaa lasten motoristen perustaitojen kehityksen – mutta kevyttäkin tarvitaan! [Brisk physical activity ensures the development of fundamental motor skills in children – but light is also needed!]. *Liikunta & Tiede, 50*(6), 47-52.

Laukkanen, A., Pesola, A., Havu, M., Saakslahti, A., & Finni, T. (2013). Relationship between habitual physical activity and gross motor skills is multifaceted in 5- to 8-year-old children. *Scand J Med Sci Sports*. doi:10.1111/sms.12116

LeGear, M., Greyling, L., Sloan, E., Bell, R., Williams, B.-L., Naylor, P.-J., & Temple, V. (2012). A window of opportunity? Motor skills and perceptions of competence of children in Kindergarten. *International Journal of Behavioral Nutrition and Physical Activity, 9*(1), 29. Retrieved from http://www.ijbnpa.org/content/9/1/29

Leonard, S. T., & Droege, M. (2008). The uses and benefits of cluster analysis in pharmacy research. *Res Social Adm Pharm, 4*(1), 1-11. doi:10.1016/j.sapharm.2007.02.001

Lindsay, R. S., Hanson, R. L., Roumain, J., Ravussin, E., Knowler, W. C., & Tataranni, P. A. (2001). Body mass index as a measure of adiposity in children and adolescents: relationship to adiposity by dual energy x-ray absorptiometry and to cardiovascular risk factors. *J Clin Endocrinol Metab, 86*(9), 4061-4067. doi:10.1210/jcem.86.9.7760

Lohmann, T. G., Roche, A. F., & Martorell, R. (1988). *Anthropometric Standardization Reference Manual*. Champaign, IL: Human Kinetics.

Lomax, R. G. (2007). *Statistical concepts: A second course for education and the behavioral sciences*. Mahwah, NJ: Lawrence Erlbaum Associates.

Lopes, V. P., Rodrigues, L. P., Maia, J. A., & Malina, R. M. (2011). Motor coordination as predictor of physical activity in childhood. *Scand J Med Sci Sports, 21*(5), 663-669. doi:10.1111/j.1600-0838.2009.01027.x

Lopes, V. P., Stodden, D. F., Bianchi, M. M., Maia, J. A., & Rodrigues, L. P. (2012). Correlation between BMI and motor coordination in children. *J Sci Med Sport, 15*(1), 38-43. doi:10.1016/j.jsams.2011.07.005

Lubans, D. R., Morgan, P. J., Cliff, D. P., Barnett, L. M., & Okely, A. D. (2010). Fundamental movement skills in children and adolescents: review of associated health benefits. *Sports Med, 40*(12), 1019-1035. doi:10.2165/11536850-000000000-00000

Malina, R. M., Bouchard, C., & Bar-Or, O. (2004). *Growth, Maturation, and Physical Activity* (2nd ed.). Champaign, IL: Human Kinetics.

Mannini, A., Intille, S. S., Rosenberger, M., Sabatini, A. M., & Haskell, W. (2013). Activity recognition using a single accelerometer placed at the wrist or ankle. *Med Sci Sports Exerc, 45*(11), 2193-2203. doi:10.1249/MSS.0b013e31829736d6

Rivilis, I., Hay, J., Cairney, J., Klentrou, P., Liu, J., & Faught, B. E. (2011). Physical activity and fitness in children with developmental coordination disorder: a systematic review. *Res Dev Disabil, 32*(3), 894-910. doi:10.1016/j.ridd.2011.01.017

Robinson, L. E. (2011). The relationship between perceived physical competence and fundamental motor skills in preschool children. *Child Care Health and Development, 37*(4), 589-596. doi:DOI 10.1111/j.1365-2214.2010.01187.x

Robinson, L. E., Stodden, D. F., Barnett, L. M., Lopes, V. P., Logan, S. W., Rodrigues, L. P., & D'Hondt, E. (2015). Motor Competence and its Effect on Positive Developmental Trajectories of Health. *Sports Med, 45*(9), 1273-1284. doi:10.1007/s40279-015-0351-6

Rodrigues, L. P., Stodden, D. F., & Lopes, V. P. (2015). Developmental pathways of change in fitness and motor competence are related to overweight and obesity status at the end of primary school. *Journal of Science and Medicine in Sport*(0). doi:http://dx.doi.org/10.1016/j.jsams.2015.01.002

Saracli, S., Dogan, N., & Dogan, I. (2013). Comparison of hierarchical cluster analysis methods by cophenetic correlation. *Journal of Inequalities and Applications, 203*, 1-8.

Schonlau, M. (2002). The Clustergram: A graph for visualizing hierarchical and non-hierarchical cluster analyses. *The Stata Journal, 3*, 316-327.

Schweitzer, L., & Renehan, W. E. (1997). The use of cluster analysis for cell typing. *Brain Res Brain Res Protoc, 1*(1), 100-108. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/9385054

Sejdic, E., Lowry, K. A., Bellanca, J., Redfern, M. S., & Brach, J. S. (2014). A comprehensive assessment of gait accelerometry signals in time, frequency and time-frequency domains. *IEEE Trans Neural Syst Rehabil Eng, 22*(3), 603-612. doi:10.1109/TNSRE.2013.2265887

Semmar, N., Bruguerolle, B., Boullu-Ciocca, S., & Simon, N. (2005). Cluster analysis: an alternative method for covariate selection in population pharmacokinetic modeling. *J Pharmacokinet Pharmacodyn, 32*(3-4), 333-358. doi:10.1007/s10928-005-0040-4

Slaughter, M. H., Lohman, T. G., Boileau, R. A., Horswill, C. A., Stillman, R. J., Van Loan, M. D., & Bemben, D. A. (1988). Skinfold equations for estimation of body fatness in children and youth. *Hum Biol, 60*(5), 709-723. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/3224965

Smidt, G. L., Arora, J. S., & Johnston, R. C. (1971). Accelerographic analysis of several types of walking. *Am J Phys Med, 50*(6), 285-300. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/5141651

Sokal, R. R., & Rohlf, J. (1962). The comparison of dendrograms by objective methods. *Taxon, 11*, 33-40.

Stergiou, N., Buzzi, U., Kurz, M., & Heidel, J. (2004). Nonlinear tools in human movement. In N. Stergiou (Ed.), *Innovative analyses of human movement* (pp. 63-90). Champaign, IL: Human Kinetics.

Stergiou, N., & Decker, L. M. (2011). Human movement variability, nonlinear dynamics, and pathology: is there a connection? *Hum Mov Sci, 30*(5), 869-888. doi:10.1016/j.humov.2011.06.002

Stodden, D. F., Goodway, J. D., Langendorfer, S. J., Roberton, M. A., Rudisill, M. E., Garcia, C., & Garcia, L. E. (2008). A developmental perspective on the role of motor skill competence in physical activity: An emergent relationship. *Quest, 60*(2), 290-306. Retrieved from <Go to ISI>://WOS:000255882500007

Tonkin, J. A., Rees, P., Brown, M. R., Errington, R. J., Smith, P. J., Chappell, S. C., & Summers, H. D. (2012). Automated Cell Identification and Tracking Using Nanoparticle Moving-Light-Displays. *PLoS One, 7*(7). doi:ARTN e40835

DOI 10.1371/journal.pone.0040835

Tremblay, M. S., Warburton, D. E., Janssen, I., Paterson, D. H., Latimer, A. E., Rhodes, R. E., . . . Duggan, M. (2011). New Canadian physical activity guidelines. *Appl Physiol Nutr Metab, 36*(1), 36-46; 47-58. doi:10.1139/H11-009

Trost, S. G., Loprinzi, P. D., Moore, R., & Pfeiffer, K. A. (2011). Comparison of accelerometer cut points for predicting activity intensity in youth. *Med Sci Sports Exerc, 43*(7), 1360-1368. doi:10.1249/MSS.0b013e318206476e

Tudor-Locke, C., Barreira, T. V., Schuna, J. M., Jr., Mire, E. F., Chaput, J. P., Fogelholm, M., . . . Group, I. R. (2015). Improving wear time compliance with a 24-hour waist-worn accelerometer protocol in the International Study of Childhood Obesity, Lifestyle and the Environment (ISCOLE). *Int J Behav Nutr Phys Act, 12*, 11. doi:10.1186/s12966-015-0172-x

Ulrich, D. A. (1985). *Test of Gross Motor Development*. Austin, TX: Pro-ed Publishers.

Ulrich, D. A. (2000). *Test of Gross Motor Development: Examiner's Manual* (2nd ed.). Austin, Texas: PRO-ED.

van Hees, V., Pias, M., Taherian, S., Ekelund, U., & Brage, S. (2010). *A method to compare new and traditional accelerometry data in physical activity monitoring.* Paper presented at the IEEE International Symposium A World Wireless, Mobile Multimedia Network.

van Hees, V. T., Gorzelniak, L., Leon, E., Eder, M., Pias, M., Taherian, S., . . . Brage, S. (2012). *A method to compare new and traditional accelerometry data in physical activity monitoring.* Paper presented at the World of Wireless Mobile and Multimedia Networks (WoWMoM), Montreal, QC, Canada.

Vlahov, E., Baghurst, T. M., & Mwavita, M. (2014). Preschool motor development predicting high school health-related physical fitness: a prospective study. *Percept Mot Skills, 119*(1), 279-291. doi:10.2466/10.25.PMS.119c16z8

Vorwerg, Y., Petroff, D., Kiess, W., & Bluher, S. (2013). Physical activity in 3-6 year old children measured by SenseWear Pro(R): direct accelerometry in the course of the week and relation to weight status, media consumption, and socioeconomic factors. *PLoS One, 8*(4), e60619. doi:10.1371/journal.pone.0060619

Williams, H. G., Pfeiffer, K. A., O'Neill, J. R., Dowda, M., McIver, K. L., Brown, W. H., & Pate, R. R. (2008). Motor skill performance and physical activity in preschool children. *Obesity (Silver Spring), 16*(6), 1421-1426. doi:10.1038/oby.2008.214

Winterstein, A. G., Johns, T. E., Rosenberg, E. I., Hatton, R. C., Gonzalez-Rothi, R., & Kanjanarat, P. (2004). Nature and causes of clinically significant medication errors in a tertiary care hospital. *Am J Health Syst Pharm, 61*(18), 1908-1916. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/15487880

Wundersitz, D. W., Gastin, P. B., Richter, C., Robertson, S. J., & Netto, K. J. (2015). Validity of a trunk-mounted accelerometer to assess peak accelerations during walking, jogging and running. *Eur J Sport Sci, 15*(5), 382-390. doi:10.1080/17461391.2014.955131