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Comparisons Between Movement Onset Identification Methods Used in Isometric Mid-Thigh Pull Test

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Comparisons Between Movement Onset Identification Methods Used in Isometric Mid-Thigh Pull Test

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A dissertation

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In partial fulfillment

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Doctor of Philosophy in Sport Physiology and Performance

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by

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December 2018

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Keywords: Movement Onset Identification, Force-Time Curve, Isometric Mid-Thigh Pull Test

ABSTRACT

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This dissertation aimed to explore the usefulness of using force derivatives for onset detection in the isometric mid-thigh pull test. First, we examined applications of three differential calculus principles, first and second derivative, and curvature using visual detection as a reference under different baseline conditions. Second, we compared the best derivative method to a threshold-based method using visual detection as a reference. Results of our first investigation showed trivial differences between many differential calculus methods and visual detection. However, statistical differences exceeding a trivial effect was observed when instantaneous force and rate of force develop were examined. Through the first investigation, first and second derivative emerged as possible viable methods for baseline with a countermovement and for all other baseline conditions, respectively. Results of the second investigation showed similarities to the first investigation with respect to onset time. However, examination of instantaneous force and rate of force development indicated that a threshold-based method tended to overestimate compared to visual detection and a first and second derivative combined method. In fact, the difference between visual detection and the first and second derivative combined method ranged from trivial to moderate under all baseline conditions while the threshold-based method often reached a large difference. Overestimation by the threshold-method was more pronounced for rate of force development. In conclusion, while not perfect, the first and second derivative

combined method appears to hold possible practical potential and may be used as an assistant method for entry-level sport scientist plus using visual detection for obvious erroneous values.

DEDICATION

This work is dedicated to my parents for their love and support.

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CHAPTER 1

INTRODUCTION

In sport performance assessment, ground reaction force is commonly used to examine athlete’s strength and explosiveness (Cordova & Armstrong, 1996; Enoka, 1979; Luhtanen & Komi, 1980; Mero & Komi, 1994; Payne, Slater, & Telford, 1968; Stone, Stone, & Lamont, 1993; Viitasalo, Salo, & Lahtinen, 1998). The isometric mid-thigh pull test (IMTP) provides ground reaction force that can be presented as a force-time curve for variables such as instantaneous force, rate of force development, and impulse (Stone et al., 1993). Many factors can be conceived that could influence validity and reliability ground reaction force variables. One such factor may be movement onset identification. Numerous studies examined different methods to identify movement onset (Bemben, Clasey, & Massey, 1990; Carlton, Kim, Liu, & Newell, 1993; Derrick, Bates, & Dufek, 1994; Dos’Santos, Jones, Comfort, & Thomas, 2017; Hanke & Rogers, 1992; Mizuguchi, Sands, Wassinger, Lamont, & Stone, 2015; Ryushi, 1988; Thompson et al., 2012; Viitasalo, 1982).

While consistent methodology appears to be lacking in the literature, visual detection of IMTP onset is commonly used in addition to newly emerging methods using a pre-defined threshold (Dos’Santos et al., 2017; Haff et al., 1997). To date, despite the increasing popularity and use of IMTP, only Dos’Santos et al attempted to examine different methods of onset detection (Dos'Santos, Jones, Comfort, & Thomas, 2017). In other fields of exercise and sport science, visual detection is considered the gold standard for onset detection (Pulkovski, Schenk, Maffiuletti, & Mannion, 2008; Staude, 2001; Teasdale, Bard, Fleury, Young, & Proteau, 1993). However, visual detection requires a trained rater and takes considerable time to complete (Dotan, Jenkins, O'Brien, Hansen, & Falk, 2016). Derivatives of force over delta time has been used to study patients’ movement in clinical settings (Heasman et al., 2000; Triolo & Lawrence, 1994). Soda et al. reported superior results by second derivative to threshold-based methods for onset detection in force and torque-time curves (Soda, Mazzoleni, Cavallo, Guglielmelli, & Iannello, 2010). To the authors’ knowledge, no studies attempted to examine application of derivatives for onset detection in the IMTP.

Consequently, this dissertation was designed to take the first step in examining usefulness of derivatives in comparison to the visual detection method for variables calculated from IMTP. The purpose of the dissertation was to inform practitioners in competitive sport of differences and similarities of onset detection methods using force derivative, pre-defined threshold, and visual examination. It is the authors’ hope that findings of this dissertation will help improve selection of onset detection method for reliability and increased rate of data return to coaches and athletes.

CHAPTER 2

COMPREHENSIVE REVIEW OF LITERATURE

There have been approximately 100 publications found in the literature that used the isometric mid-thigh pull test (See Table 1.1, Appendix A). In 1997, Haff et al. published the very first study that used the isometric mid-thigh pull test. Between the time of the first publication and 2010, there were approximately 6 studies published with the isometric mid-thigh pull test. Between 2010 and 2015 alone, approximately 16 studies were published. Finally, within the last three years, approximately 58 studies were published. With an increase in the popularity of the test, variation in the testing protocol such as positions (Beckham, Sato, Mizuguchi, Haff, & Stone, 2018; Dos'Santos, Thomas, Jones, McMahon, & Comfort, 2017) and analysis procedures such as onset detection (Dos'Santos, Jones, Comfort, & Thomas, 2017) have begun to be observed. While the increasing popularity of the test itself may imply an increasing interest in sport science, increasing variation in the methodology of the isometric mid-thigh pull test, whether it is a testing protocol or analysis procedure, may imply researchers' and sport scientists' efforts to improve the effectiveness of the test in practical settings, besides potential problems such as difficulty comparing results from different studies in research. One such aspect of the methodology that can be further examined is how the onset of a pull is detected. Of many publications using the isometric mid-thigh pull test, approximately 50% of the publications used time-dependent variables such as forces at pre-defined time points and rate of force development over pre-defined time windows from the onset of a pull (Table 1.1). Because these time-dependent variables are defined in relation to the onset of a pull, it appears logical to rationalize that valid and reliable detection of the onset of a pull plays an important role for these variables. Thus, the objectives of this review were 1) to review onset detection methods that have been reported for the isometric mid-thigh pull test and 2) to seek other potential onset detection methods that are practical for sport science in order to provide practitioners and researchers with possible options to consider when using the isometric mid-thigh pull test.

Current Analysis Method of Movement Onset Detection for the IMTP

Recently, Dos'Santos et al. (2017) have pointed out the lack of consistency in how the onset of a pull has been detected in the isometric mid-thigh pull test literature. Some studies used simple visual detection of the onset while others used a pre-determined force threshold (Table 1.1). Yet, other studies did not report how the onset was detected. For example, the very first study on the isometric mid-thigh pull test by Haff et al. (1997) used visual detection. In 2017, the literature began to observe more studies that used a threshold of some kind (Brady, Harrison, Flanagan, Haff, & Comyns, 2017). A threshold was defined as an absolute or relative force value above the baseline force level or a relative force level such as 5% of the baseline force level (or body weight) or five times standard deviation of the baseline force level above the mean baseline force level (Dos'Santos et al., 2017). It is also worth noting that many publications share the same authors and/or are their data were collected by the same laboratory. These publications are speculated to have used the same methodology in the onset detection. Nonetheless, the onset detection method appears to be mostly visual detection or use of a threshold.

While the lack of consistency in reporting does not necessarily mean that one method is substantially more valid and/or reliable than others, it can be argued that the presence of many different methods can at least lead to confusion. Furthermore, the testing protocol itself could not remain thoroughly as the very first IMTP test because the protocol was varied and accommodated to the method of onset detection used specifically in each study. In 2017, Dos'Santos et al. reported results of comparing different thresholds for onset detection. They concluded the study by recommending the use of five times the standard deviation of the baseline force level above the mean baseline force level (Dos'Santos et al., 2016). In this study, movement or force undulation during the baseline period was controlled by the investigators (peak deviation >50N from mean baseline force level) to produce a level, straight baseline, which was speculated to be important to keep the baseline force level below the threshold when the pull had not begun. Control of movement or force undulation also extended to a countermovement, where a visible countermovement resulted in a false trial. On the other hand, Beckham et al. (2012), five years prior to the study by Dos'Santos et al., allowed for a countermovement up to approximately 200N from the baseline. While an effort was made in the study to minimize a countermovement and reduce the baseline force undulation, practicality of the test to be implemented with a large group of athletes was considered an important aspect of the testing protocol.

To date, only one study by Dos'Santos et al. has attempted to examine different onset detection methods in the isometric mid-thigh pull test. Even the Dos' Santos et al. study compared different thresholds and did not examine visual detection or any other types of detection methods. At this point, if the isometric mid-thigh pull test is to gain greater credence as a test in practical and research settings with athletes, knowledge of differences and similarities of different detection methods are necessary.

Common Methods for Movement Onset Detection

Onset detection does not appear to be anything new to the literature of sport science, exercise science, and biomechanics (See Table 1.2, Appendix B). In measurements made with devices such as electromyography, force plates, and isometric and isokinetic machines, numerous attempts have been made to compare different onset detection methods. Each device and testing protocol are likely to yield unique time-series data. Thus, an onset detection method should consider unique characteristics of a given set of time-series data. However, simultaneously, there may be common underlying features of known onset detection methods that can be adopted in the onset detection of force-time curves generated from the isometric mid-thigh pull test. Here, we review common onset detection methods that have been reported in the literature.

Visual Detection

Perhaps, the oldest and most traditional method of onset detection is one performed by a trained rater through visual examination of plotted time-series data. Visual onset detection has often been argued to be the "Gold Standard" in electromyographic and torque/force time-series data (Tillin, Jimenez-Reyes, Pain, & Folland, 2010; Tillin, Pain, & Folland, 2013). Cited benefits of visual onset detection include greater validity and reliability than automated methods using a threshold (Tillin et al., 2010; Tillin et al., 2013). For example, Pain et al. (Pain & Hibbs, 2007) shared their laboratory validation results that compared a threshold-based method, visual detection, second derivative-based method, and a wavelet-based method. The validation effort utilized simulated data with added random noise, in which an actual onset was known. The results they shared indicated visual detection as one of the most valid methods. Proponents of automated methods appear to argue that the visual detection method is more subjective and has lower reliability (G. Staude & Wolf, 1999; Thompson et al., 2012). However, Tillin et al. (Tillin et al., 2010; Tillin et al., 2013) provide a compelling argument with data that visual detection method can have minimal subjectivity and high inter-rater (variation of 1.23 ms over onset time) and intra-rater reliability (variation of 0.97 ms over onset time) if a systematic approach is to be followed. They outlined and used a systematic approach in an isometric knee extension exercise as 1) use of a trained rater, 2) use of trials with stable baseline force (>0.5N in the preceding 100ms) assuming that little force is exerted yet, 3) viewing signals with a consistent scale, and 4) use of a robust definition of onset such as the last trough within the envelope of the baseline noise (Tillin et al., 2013). Dotan et al. (Dotan, Jenkins, O'Brien, Hansen, & Falk, 2016) argue that the primary drawback of visual detection is the time that it takes.

While each combination of a testing modality and protocol is likely to produce unique time-series data, it is not surprising to observe multiple studies using visual detection for data analysis of the isometric mid-thigh pull test as used in other types of measurement (Table 1.1). Given the outlined systematic approach by Tillin et al. (Tillin et al., 2013), the primary challenge in applying visual detection in the isometric mid-thigh pull test appears to be establishing a stable baseline with force fluctuation less than 0.5 N in the preceding 100ms. This challenge arises from the fact that an athlete must stand on a force plate and hold the power position. While no published data appear to exist on an expected amount of baseline force fluctuation, we speculate, based on our experience in our laboratory, that maintenance of such low force fluctuation as 0.5N is difficult and is perhaps impractical while holding the power position. Dos’Santos et al. (Dos'Santos, Jones, et al., 2017) described their effort to keep baseline force fluctuation under 50N of mean system weight recorded on a force plate prior to the onset of a pull. While 50N may be a more feasible amount of fluctuation, our experience in conducting over 1000 isometric mid-thigh pull trials with athletes every year has indicated that it is practically difficult for some athletes to maintain a clean baseline such as those described above, let alone to avoid a small amount of countermovement. While an effort to maintain a clean baseline should not be neglected especially if the isometric mid-thigh pull test is to be used for research purposes, it is also important to recognize that sport science needs to accommodate athletes if it aims to help athletes. In light of this principle in sport science, if the isometric mid-thigh pull test is to be used frequently as a monitoring tool for athletes, consideration of practicality appears important and both the testing protocol and analysis procedures should be appropriately adapted.

Given the importance of practicality, in our laboratory, the visual detection method currently follows the following systematic approach: 1) use of a trained rater, 2) viewing signals with a consistent scale (approximately 2500 to 3000 ms), and 3) use of a robust definition of onset (the trough of a countermovement if any or the first edge of the last pixilation of the baseline that is at the beginning of a continuous rise. When there is a high amount of noise, particularly high frequency noise, in data, a zero-lag low pass Butterworth filter with the cutoff frequency of 10Hz is applied first (Tillin et al., 2013). Use of a scale that is larger than that suggested by Tillin et al. (Tillin et al., 2013) is necessary because of the need to differentiate between an actual pull and inevitable movement while attempting to hold the power position.

Threshold-Based Method

There have been numerous published studies that attempted to examine different thresholds for onset detection (Table 1.2). Thresholds are used in such a way that the point at which a signal level passes above or below a threshold depending on the type of time-series data is marked as the onset. Thresholds appear to be categorized into two groups – absolute threshold and relative threshold (Dos' Santos, Thomas, Jones, & Comfort, 2018; Dos’Santos, Thomas, Comfort, McMahon, & Jones, 2017; Dotan et al., 2016; James, Roberts, Haff, Kelly, & Beckman, 2017; Oranchuk, Robinson, Switaj, & Drinkwater, 2017). Absolute thresholds use a pre-set value for all trials such as 4Nm in an isometric contraction test (Dotan et al., 2016). Relative thresholds use a value based off of a unique characteristic of each trial. For example, a certain percentage of maximum voluntary contraction torque level (e.g. 5%) (Dotan et al., 2016) and two times standard deviation beyond the baseline mean (Hodges & Bui, 1996) have been used as a threshold. Testing modalities and protocol and investigators' preference appear to dictate how a threshold is set.

In general, threshold-based methods appear to perform inferiorly to other methods (Dotan et al., 2016; Pain & Hibbs, 2007; P. Soda, S. Mazzoleni, G. Cavallo, E. Guglielmelli, & G. Iannello, 2010; Tillin et al., 2013). However, Pain et al. (Pain & Hibbs, 2007) reported that visual detection was more accurate overall than a threshold-based method. Other studies reported inferiority of a threshold-based method such as higher variability and systematic error when a threshold-based method is used (Dotan et al., 2016; P. Soda et al., 2010). For example, Dotan et al. (Dotan et al., 2016) compared a threshold-based method to visual detection method on an explosive isometric knee extension exercise. They used an absolute threshold of 4 Nm and a relative threshold of 5 % maximum voluntary contraction. Their results indicated that the threshold-based onset times were up to 40.3 ms different from visual detection. Soda et al. (P. Soda et al., 2010) estimated the probability of correctness for a number of different onset detection methods. The examined methods included 5 different threshold-based methods that used relative thresholds (2, 4, 6, 8, and 10% of peak force and torque) for onset detection during various tasks. Their results showed that the probability of correctness of these threshold-based methods ranged from 77.6 to 79.6%. In their study, methods based on second derivative and probability density function appeared to perform better.

Of many studies that used the isometric mid-thigh pull test, nine studies (Brady et al., 2017; Dos' Santos, Lake, Jones, & Comfort, 2018; Dos' Santos, Thomas, et al., 2018; Dos' Santos, Thomas, Jones, McMahon, & Comfort, 2017; Dos'Santos et al., 2016; Dos'Santos et al., 2017; James et al., 2017; Oranchuk et al., 2017; Thomas, Dos’Santos, Comfort, & Jones, 2017) reported to have used a threshold-based method for onset detection. The thresholds used in these studies included both absolute and relative thresholds such as 20 and 40N (Dos' Santos, Thomas, et al., 2018; James et al., 2017) as an absolute threshold and 5% of baseline force and five times baseline standard deviation above mean baseline force (Dos' Santos et al., 2017; Oranchuk et al., 2017). In 2017, Dos’Santos et al. published a study that compared test-retest reliability of different thresholds. They reported that five times baseline standard deviation above mean baseline force was the most reliable of all thresholds examined. To date, this appears to be the only study in the literature that examined onset detection methods in the isometric mid-thigh pull test.

Other Methods

In addition to visual detection and threshold-based methods, attempts have been made to use yet different methods (Table 1.2) borrowing from different disciplines such as mathematics and statistics (De Ruiter, Vermeulen, Toussaint, & De Haan, 2007; Ghez, Hening, & Favilla, 1989; Heasman et al., 2000; Ikemoto, Demura, & Yamaji, 2004; Liebermann & Goodman, 2007; Paolo Soda, Stefano Mazzoleni, Giuseppe Cavallo, Eugenio Guglielmelli, & Giulio Iannello, 2010; Triolo & Lawrence, 1994). While some methods appear specific to a modality and a testing protocol, some appear to have potential for application for force-time curves from the isometric mid-thigh pull test. Considering the degree of complexity for practicality, a group of methods relying on mathematical principles are reviewed below. While statistical methods appear as common or more examined than mathematical methods, applications of these methods may pose a substantial practical challenge due to its complexity in applying and setting up an automated computer algorithm.

Mathematical Methods

A group of mathematical methods, with apparent potential, relies on principles used in calculus (De Ruiter et al., 2007; Ghez et al., 1989; Heasman et al., 2000; Triolo & Lawrence, 1994). In mathematics, the baseline of an isometric mid-thigh pull force-time curve prior to the onset of pull can be considered a form of random data (Bendat & Piersol, 2011). Various geometric characteristics of a curve consisting of random data such as a critical point, an inflection point, and curvature can then be calculated using principles of differential calculus (Begg & Rahman, 2000; Ghez et al., 1989; Kamimura, Yoshioka, Ito, & Kusakabe, 2009). When applied to a force-time curve, differential calculus begins with a quotient of the change of force over the corresponding time period (i.e. derivative). In net effect, differential calculus examines the slope of a tangent line in different orders of derivatives or other characteristics related to the slope (Example in Figure 2.1). While higher order derivatives are used in many disciplines of science such as engineering, first and second order derivatives appear most common in the field of exercise and sport science.

Given a specific time point t0 in a force-time curve, the first derivative of force is defined using the following equation.

$$f'_{(x_0)} = \lim_{x \to x_0} \frac{f(x) - f(x_0)}{x - xo} = \lim_{\Delta x \to 0} \frac{f(x_0 + \Delta x) - f(x_0)}{\Delta x}$$

Equation 1.1 The definition of first derivative equation. $f'_{(x_0)}$, first derivative at the function f of the point xo ; $\lim_{x \to x_0}$, the independent variable x approaches xo ; Δx, the difference between x and xo . The equation was referenced from Canuto and Tabacco (Claudio & Anita, 2008).

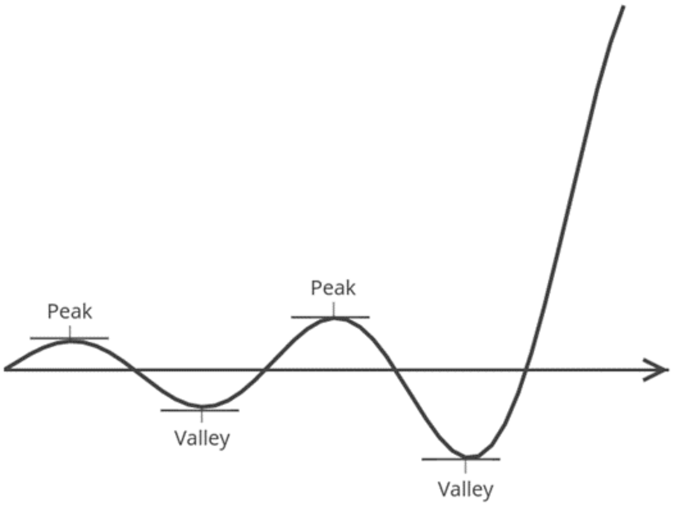

Figure 2.1 A function f(x) has several peak and valley geometrically to reflect the change of dependent variable. The critical points can be found by first derivative calculation (Claudio & Anita, 2008).

Calculation of first derivative provides a couple of benefits. 1) The positive sign of the slope of a tangent line at a given point on a curve indicates that the curve has an upward trend (i.e. increasing). 2) The negative sign of the slope then indicates a downward trend in the curve (i.e. decreasing). 3) Consequently, when the slope of a tangent line changes from the positive to negative sign or vice versa, the point of change (e.g. zero first derivative) is called a critical point and can be used as an indicator that the curve has changed its direction of trend (Figure 2.2).

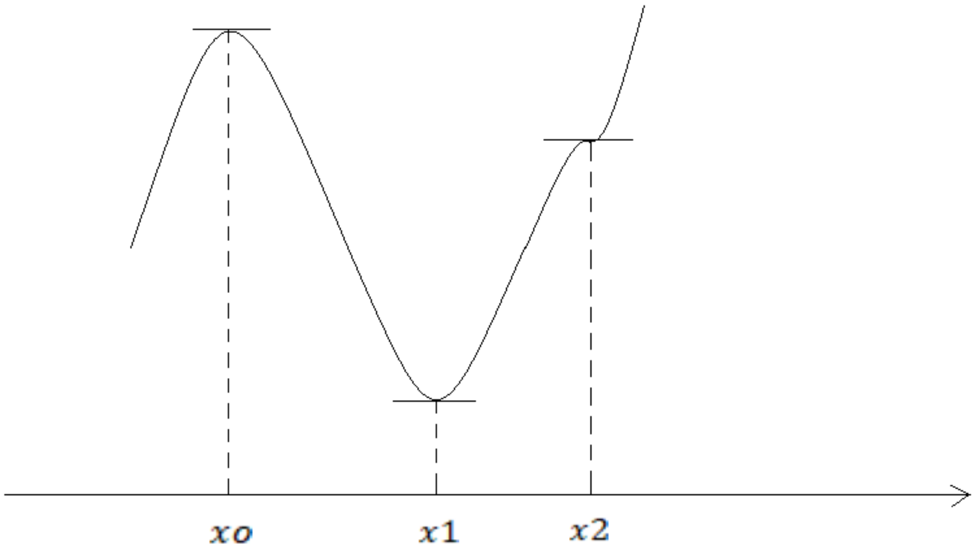

Figure 2.2 Critical points x0, x1, x2 on a curve. A critical point is a point where first derivative crosses zero (Claudio & Anita, 2008).

The idea of critical points on a force-time curve has been used to recognize the transition during movements (Begg & Rahman, 2000; Ghez et al., 1989; Kamimura et al., 2009). In onset detection, Tillin et al. (Tillin et al., 2013) argue that first derivative of a force-time curve can provide accurate onset detection when time-series data have to be filtered due to the presence of high frequency noise. In this situation, they argue that the last point at which the first derivative of a force-time curve crosses zero can be used as an onset.

Following first derivative, second derivative can be calculated (Equation 1.2).

$$f''_{(x_0)} = (f')'(x_0)$$

Equation 1.2 The mathematical definition of second derivative. f'’(x0), second derivative at the point x0 of the function f; (f')’(x0), first derivative of the first derivative of function f of the point x0 (Claudio & Anita, 2008).

Second derivative is the slope of a tangent line of the first derivative curve. An inflection point (Figure 2.3) is a point where the slope of a tangent line equals 0. An inflection point is associated with concavity of a curve. An inflection point signals a point at which a curve changes its shape from concave to convex or vice versa. Application of second derivative to times-series data such as a force-time curve can reveal the number of concavities or the extent of flatness of the curve. Soda et al. (2010) examined use of second derivative for onset detection in force and torque-time curves of various tasks. Their methodology consisted of applying a low-pass filter at 3 or 5 Hz of cut-off frequency and calculating the first derivative, from which the second derivative was calculated. Once the second derivative was calculated, a computer can be programmed to find the nearest peak in the second derivative as an onset. They also examined a method in which the first point at which second derivative crossed zero, while reading backwards from a point during a task, was identified as an onset. Their results indicated that these methods had the probability of correctness ranging from 82.2 to 89.3% compared to the set number from onset time while thresholds method based on arbitrary threshold values had 72.9 to 79.6% of the probability of correctness.

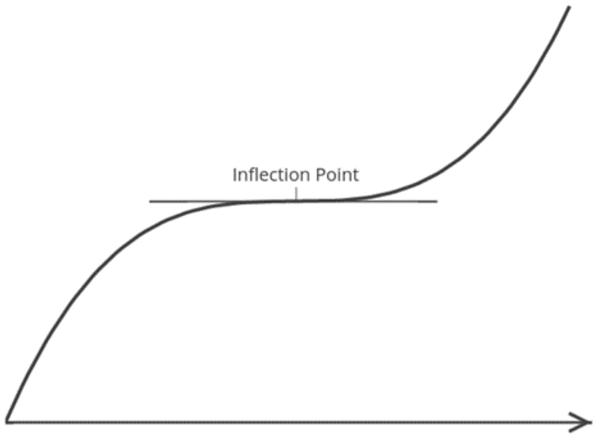

Figure 2.3 The example of second derivative application on curves. (Claudio & Anita, 2008).

While not common in the field of exercise and sport science, curvature in differential calculus may also be useful in detecting an onset. A given point on a curve with a sharp change of direction is indicated by a drastic change in the degree of the bend in a curve. Basically, the curvature of a curve at a given point is inversely proportional to the radius of a circle drawn on the curve through the point (Figure 2.4). The radius of the circle (i.e. the circle’s size) is determined in such a way that both the circle and the portion of the curve at the point share the same tangent line. The curvature at a given point on a curve is calculated using Equation 1.3.

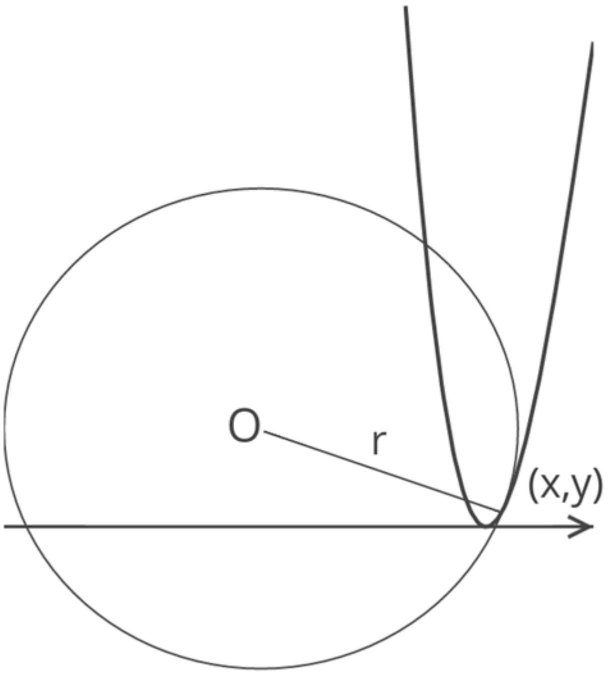

Figure 2.4 Curvature on the point (x, y) of a curve (Yates, 1947)

$$K = \frac{f''(x_0)}{\left(1 + f'(x_0)^2\right)^{3/2}}$$

Equation 1.3 Curvature of a singular point. Equation was from Yates (Yates, 1947). K, curvature value; $f''(x_0)$, second derivative of the function $f(x)$ at x_0; $f'(x_0)$, first derivative of the function $f(x)$ at x_0.

In biomechanics, curvature has been used as a method to find a point of change on a curve (Kaminski & Gentile, 1986; Morgan & Proske, 1984; Rivera-Alvidrez, Kalmar, Ryu, & Shenoy, 2010). Using curvature, one may look for a change in movement trajectory such as an onset point (Kaminski & Gentile, 1986). While the theory exists, there do not appear to be any studies that attempted to examine the validity and reliability of the use of curvature for onset detection.

In conclusion, the issue of onset detection in time-series data is not new to the literature of sport and exercise science. Visual detection still appears to be considered the “Gold Standard”. However, because of the need of a trained rater and more time to complete analysis, many have attempted to come up with an automated method for onset detection. Automated methods have ranged from simple use of a threshold to application of complex mathematical techniques such as wavelet transform (Soda et al., 2010; Teasdale, Bard, Fleury, Young, & Proteau, 1993) to yet complex statistical techniques such as computation of maximum likelihood estimate (Gerhard Staude, Flachenecker, Daumer, & Wolf, 2001; G. H. Staude, 2001). While some methods have seen some success, Soda et al. may make a valid point that each method is suited for a certain situation or time-series data with a set of certain characteristics (P. Soda et al., 2010). In this regard, they have suggested use of a computerized decision-making algorithm to select the most appropriate method and demonstrated that such approach can be superior to use of any single onset detection method.

It appears that the isometric mid-thigh pull test is gaining acceptance with more and more studies using the test (Table 1.1). While perhaps the gold standard method of onset detection may also remain to be visual detection for the isometric mid-thigh pull test as in other modalities and tests, the emergence of studies using threshold-based methods likely implies that automated methods are sought after perhaps due to perceived objectivity, accuracy, and reliability and/or an attempt to speed up the analysis procedure. With only one study having attempted to compare different onset detection methods for the isometric mid-thigh pull test (Dos'Santos, Jones, et al., 2017), there may be a need for more research on how different methods of onset detection perform with time-series data from the test. While attempting to examine different methods, we believe that it is important that the practicality of a method is always considered if the isometric mid-thigh pull test is to be used as an athlete monitoring tool in practical settings. Techniques that rely on complex mathematical or statistical techniques may prove to be more valid and reliable. However, if these techniques require special knowledge and skills to implement, they may not be useful for coaches and sport scientists. In light of this concept, methods relying on thresholds and simpler mathematical techniques such as derivatives can prove to be effective and useful.

CHAPTER 3

COMPARISON OF ONSET MOVEMENT IDENTIFICATION BETWEEN NUMERICAL ANALYSES AND VISUAL ANALYSIS IN ISOMETRIC MID-THIGH PULL TEST

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Brief running head: Movement onset detection

Abstract

The objective of the study was to examine movement onset identification differences between numerical analyses and visual analysis in the isometric mid-thigh pull test. Five numerical analyses (first derivative, second derivative forward/backward, curvature forward/backward) were used to analyze the force-time curve for onset time and instantaneous kinetic variables compared to the visual analysis results. Eighty independent trials were categorized into four groups based on baseline undulation by standard error of estimate: SEE<15N, SEE 15-30N, SEE>30N or an observed countermovement. Mixed ANOVA tests showed a statistical main effect for analysis methods ($p < 0.001$) for onset time, while an interaction effect for baseline undulation by time phase ($p = 0.001$) for instantaneous force and rate of force development ($p<0.001$). For the onset time, all numerical methods except second derivative forward were statistically different ($p<0.001$) from the visual analysis although all had a trivial difference from visual analysis ($d<0.05$). For instantaneous force, a trivial difference was observed between the first derivative and visual analysis under the countermovement ($d<0.01$) and a small to moderate difference between the second derivative forward and visual analysis under undulating baseline with no countermovement ($d<1.00$). A method using both first derivative and second derivative forward may prove to be useful in practical settings for onset detection in the isometric mid-thigh pull test, depending on the presence of a countermovement.

Key words: calculus; curvature value; visual analysis; force-time curve; analysis

INTRODUCTION

Examination of biomechanical variables such as force and rate of force development (RFD) has been considered crucial in sport performance assessment. Various biomechanical variables can be used to understand and monitor an athlete's performance (1, 13). Currently, multiple tests (isometric single leg test, isometric squat, isometric mid-thigh pull) have been developed for biomechanical performance assessment. From these tests, variables such as single point force and RFD over various time periods can be obtained via a computer processing system (1, 9, 13, 23). Accurate quantifications of these time-dependent variables rely on identification of a movement onset. Multiple methods of movement onset identification have been developed in an attempt to improve identification accuracy under different conditions (7, 8, 9, 12, 18, 19, 21, 23).

Biomechanical assessment of sport performance often dependents on transformation of analogue signals into their digital counter-parts. For example, signals of common interest include ground reaction force usually presented as a time-series waveform (i.e. a force-time curve) (21). Signals theoretically consist of a number of input signals with various frequencies that are often normally distributed when there is no interpolation. Human movements produce signals with unique frequencies that alter the mean value of the normally distributed frequencies. Identifying the shift in the mean value of normally distributed signal frequencies can provide a movement onset given that a proper cut-off is chosen. However, such dependency on a cut-off can still lead to error in movement onset detection as there appears to be no consensus in how to choose a proper cut-off.

In the current literature on the isometric mid-thigh pull test, visual analysis has been commonly used as a method for movement onset identification (2, 3, 9, 10, 20). Staude et al. (2001) reported a small estimated error for movement onset identification between visual analysis and the aforementioned signal frequency-based method in biomechanical tests. Visual analysis has some limitations. One such limitation is required training of a rater performing visual analysis as raters with no to limited experience often do not appear reliable (6). Furthermore, visual analysis takes more time as a rater must analyze each trial. Therefore, a computer-based automated or semi-automated analysis method can prove to be effective in practical settings if at least it performs comparably to visual analysis.

Previous studies hinted on the possible use of numerical methods for time-series waveforms for identification of movement onset (4, 25, 8, 11, 12, 15, 16, 19, 25). Two categories of numerical methods have been examined to analyze time-series waveforms. Basically, the two categories are calculus principle methods that use first and second derivatives to find critical and inflection points (4, 8, 11, 12, 19, 25, 26), or geometric principle methods that use curvature values at each data point (12, 15, 16). Critical points from calculus principle methods have previously been used in an attempt to identify movement onset (8, 12, 19). However, to date, there appear to be no attempts to examine applicability of the numerical methods for the isometric mid-thigh pull test.

Thus, the objective of the present study was to apply numerical methods to the analysis of the isometric mid-thigh pull force-time curves and compare the results to those of visual analysis for compatibility. The study is intended to inform practitioners of the comparability between numerical and visual analysis methods for movement onset identification. The information should help them choose an analysis method suitable for their settings.

METHODS

Experimental Approach to the Problem

The present study was designed to examine two factors: 1) differences over onset time and kinetic variables (force and rate of force development) between numerical method and the visual analysis method; 2) whether the differences have any associations with characteristics of the baseline prior to the approximated point of onset movement in an isometric mid-thigh pull. These characteristics of the baseline are 1) any countermovement defined as any visible presence of a downward inflection in the force-time curve baseline that continued into a rise of force due to the action of an isometric pull and 2) the degree of undulation in the baseline when there is no countermovement. These characteristics were chosen for comparison based on the experience of visual analysis that measurement of kinetic variables correlated with the onset movement while the shape of baseline affected the onset movement identification in visual analysis.

To examine the two factors above, a total of 80 independent trials belonging to 80 subjects were selected from our long-term athlete monitoring archive. These 80 trials were selected such that there would be four groups of 20 subjects. These groups were created based on the two baseline characteristics. If a trial had a countermovement, the athlete of the trial was placed into the countermovement group. If a trial did not have a countermovement, the baseline was evaluated for its level of undulation. This evaluation was accomplished by first applying the best fit linear trend line through the baseline for 1.5 seconds prior to an approximated point of the onset of an isometric pull and then calculating a standard error of estimate (SEE) associated with the best fit linear trend line. The line and SEE were used over a mean and standard deviation of the baseline force because the use of a mean and standard deviation would overestimate the level of undulation if the baseline had an upward or downward trend. Trials without a countermovement were then placed into the remaining three groups based on the following three levels of baseline undulation: SEE <15 N (8.10±3.38 N), SEE from 15 to 30 N (18.98±3.63 N), and SEE > 30 N (47.25±18.68 N) (Figure 3.1).

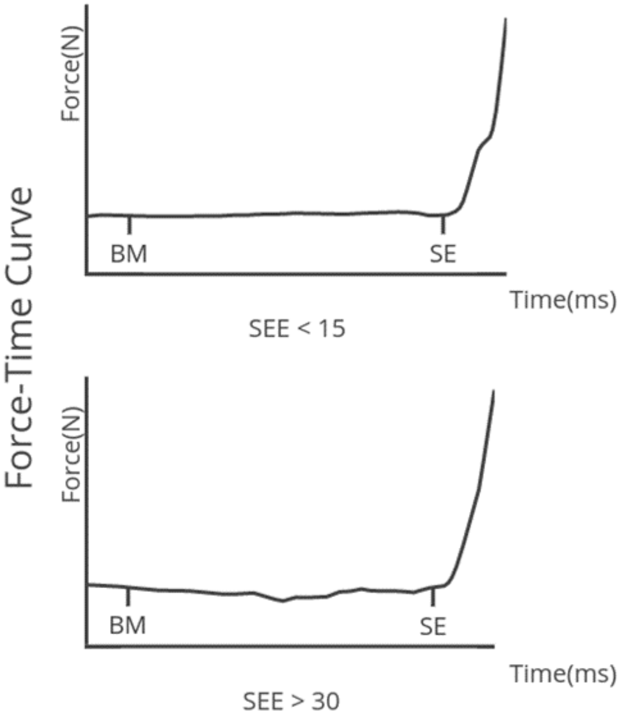

Figure 3.1 Examples of four baseline characteristics. BM: the start of the baseline measurement; SE: an approximated onset point of a pull. Time from BM to SE was 1500ms.

Subjects

Eighty independent samples (Table 3.1) were selected based on the criteria in such a manner that there would be 20 samples for each of the four groups. Furthermore, each group included subjects from at least four sports and up to five sports. (Table 3.1). All samples were retrieved from the on-going athlete monitoring program repository in the Department of Sport and Exercise Laboratory of East Tennessee State University. The study was approved and granted a waiver for informed consent by Institutional Review Board at the university.

Table 3.1 Characteristics of subjects.

SEE	Age (yrs)	Height (cm)	Mass (kg)	Sports	Peak Force (N)
< 15	20.4±1.3	171.5±12.0	72.0±14.6	Soccer: 2 males, 3 females, Basketball: 2 males, Tennis: 3 males, 3 females, Volleyball: 3 females, Softball: 4 females	3043±865
15 – 30	20.4±1.5	174.4±8.4	78.8±15.1	Soccer: 2 males, 4 females, Basketball: 2 males, 3 females, Tennis: 2 females, Softball: 3 females, Volleyball: 4 females	3293±823
>30	20.8±1.5	176.0±7.1	74.6±6.6	Soccer: 4 males, 4 females, Volleyball: 5 females, Tennis: 5 males, Baseball: 2 males	3809±1245
Countermovement	21.1±1.6	178.4±10.7	76.7±12.0	Soccer: 5 males, 2 females, Basketball: 3 males, 2 females, Volleyball:3 females, Tennis: 3 males, 2 females	3240±566

*Peak force was the maximal force value during the isometric mid-thigh pull.

Procedures

Testing Equipment

Data were collected as previously described (9, 10, 20) using a pair of uni-axial force plates placed side by side (Rice Lake Weighing Systems, Rice Lake, WI). Analog voltage signal from the force plates were sent to an amplifier (Temecula, California) and digitized using LabView by National Instruments (Austin, TX). The digitized data were then manipulated using a custom-made program to produce a force-time curve for further analyses.

Isometric Mid-Thigh Pull Testing Protocol

The protocol began with warm-up as described previously (9, 10, 20). Subjects were then placed inside a customized power rack in the power position with clean grip width on a pair of force plates placed side by side (3, 9). Wrist straps and tapes were used to secure the hands onto an immovable bar because grip strength is often the limiting factor in producing greater force. Subjects were instructed to exert slight pulling tension onto the bar to remove tissue slack in order to minimize a position change during an actual trial. Two warm-up trials were given at perceived 50 and 75% of maximal effort (3). In maximal trials, Subjects were told to pull 'as fast and as hard as possible' until two trials differing no more than 250N in peak force were obtained (3). An unobserved countermovement with force downward trending from baseline less than 200N was included. However, for the sake of this study, only one trial was used as averaging multiple trials would reduce error, which was of interest in this study.

Variables

From a force-time curve of each trial, the following variables were obtained using each analysis method: onset time, forces at 50, 90, 200, and 250ms, and RFD over 50, 90, 200, and 250ms windows. These variables were chosen due to their common use in the isometric mid-thigh pull test (9, 10, 20). Onset time was defined as the beginning of an isometric mid-thigh pull on a force-time curve. This was measured as time elapsed from the point at which the computer was initiated to record incoming voltage signal from the force plates. Forces at the four different time points were defined as an instantaneous force at the respective time from the onset time. RFD over the four different time windows were defined as a change in force over the respective time window divided by the time elapsed in seconds.

Force-Time Curve Analyses

Six different methods were employed to analyze the 80 trials: visual analysis method, first derivative analysis method, second derivative forward analysis method, second derivative backward analysis method, curvature forward analysis method, and curvature backward analysis method. For all methods, data were filtered using the 2nd order Butterworth low pass digital filter with the cutoff frequency of 10Hz to minimize electrical noise in the data.

Visual Analysis Method

The traditional visual analysis method was performed by a rater experienced in analyzing isometric mid-thigh pull force-time curves. An onset time was found for each trial by visually identifying a point at which the force-time curve continuously and rapidly arises. The reliability report by the visual method on kinetic variables of force and rate of force development measurement remained over 0.8 (3, 9, 10, 20). If there was a countermovement, the bottom of the inflection caused by the countermovement was used as the onset point. In order to standardize pixelation on a computer screen, approximately 2.5 seconds of each curve including the baseline and onset point were displayed on the same screen with no change in resolution setting. Upon identification of an onset point, the remaining variables were calculated. A custom-made computer program using LabView (ver. 2010) was used for the visual analysis method.

Furthermore, filtered force-time curve data in the custom-made program were exported for the other analysis methods using MatLab (Version 2015, The MathWorks, Inc., Natick, Massachusetts) to ensure that possible differences in computer algorithm used in the analysis steps such as filtering would not cause differences in the variables between the methods. Peak force values were compared between the two software programs to ensure that identical force values were used.

First derivative analysis method

First derivative by calculus principle was applied in MatLab to each force-time curve exported from the custom-made LabView program. The use of first derivative allowed us to identify every critical point (i.e. peak and valley in a force-time curve) and the duration between each critical point (Figure 3.2). The longest section of a force-time curve between two adjacent critical points with a positive slope of its tangent line was then marked as an escalating period (e.g. a period during which force arose rapidly). The very first data point during this escalating period was identified as the onset time. Upon identification of an onset time, the remaining variables were calculated. Each escalating period was also used in the remaining methods as a reference. Good between-trial reliability had reported from 0.74 to 0.96 for the instantaneous force at 50ms and 100ms, respectively (23).

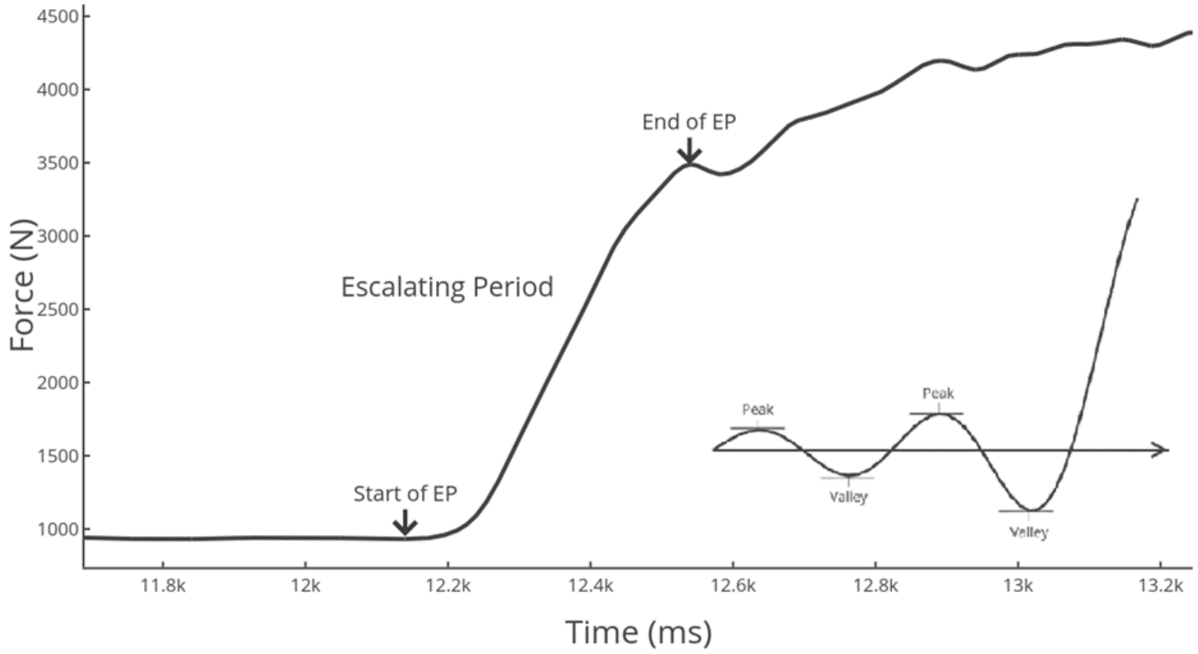

Figure 3.2 Example of a time-series curve with peaks and valleys identified using first derivative. A section between a pair of adjacent peak and valley has a set of tangent lines with the same sign (positive or negative) for the slope. The longest section with a set of positive slopes is the escalating period (i.e. from the last valley 'Start of EP' on to the next peak of the curve 'End of EP'). The gap on the picture shows the period from the peak to the valley in the real data collection.

Second derivative analysis methods

Second derivative of calculus was applied in two different ways to identify an onset point. Using the escalating period found in the first derivative method, a computer algorithm was written to read the data points of plotted second derivative forward (i.e. chronological order) or backward (i.e. reverse chronological order) from the beginning of the escalating period. The forward (second derivative forward) and backward (second derivative backward) readings then looked for the first inflection point as the onset time but in the opposite directions. The method has used in the study to identify the movement onset, though no reliability reported in the study (17). Another statistical comparison of probability of correctness to the set number of onset time was made and it showed a 82.2% to 89.3% chance of having the same value as the set number.

Curvature analysis methods

To apply curvature of calculus, the escalating period from the first derivative analysis method was again used. Within the escalating period, curvature was calculated. A computer algorithm was written to detect the first point at which the curvature value exceeded 100 while reading forward (curvature forward) and backward (curvature backward) as with the second derivative analysis methods. The cutoff curvature value of 100 was chosen based on our pilot study.

Statistical Analysis

Data were first screened for outliers and normal distribution. Outliers were checked for within each group using 2.58 multiplied by the standard deviation. Following screening, a two-way mixed ANOVA was performed with the dependent variable being onset time and the independent variables being group (4) and analysis method (6). This omnibus ANOVA was performed to examine 1) whether there were differences between any of numerical methods and the visual analysis method and 2) whether the differences were dependent on the characteristics of the baseline. Thus, the post hoc tests focused on breaking down the interaction effect using interaction contrasts with Scheffe adjustment. Following the first ANOVA, two three-way mixed ANOVAs were performed with the dependent variables being the instantaneous force and rate of force development and the independent variables being group (4), analysis methods (6), and times from the onset (4). The focus of the omnibus ANOVAs was to examine whether a difference between any of the numerical methods and the visual analysis method was dependent on the baseline characteristics and time from the onset. Thus, statistical interaction effects were broken down to interaction contrasts in the post hoc analyses with Scheffe adjustment. In addition, Cohen's d was calculated (a mean difference divided by a pooled standard deviation) where appropriate to examine a practical magnitude of difference (Effect size: trivial = <0.1, small = 0.2-0.6, moderate = 0.6-1.2, large = 1.2-2.0, and very large = 2.0-4.0) (5, 14). The initial critical alpha level was set at 0.05. All statistical analyses were conducted using SPSS ver. 20 (An IBM company, New York, NY) with exception of Cohen's d, which was calculated using Excel (Microsoft, Redmond, WA).

RESULTS

Onset Time Analysis

Following the application of Greenhouse-Geisser adjustment due to the violation of sphericity, the two-way mixed ANOVA showed only a statistical main effect for the analysis method ($F_{(1.371,\ 104.211)}$ = 311.221, $p < 0.001$) in the onset time. Post hoc pairwise comparisons using Bonferroni adjustment for the main effect of the analysis method showed a statistical difference between all the methods except for the comparison between the visual analysis and the second derivative forward analysis (p=1.000) (Figure 3.2).

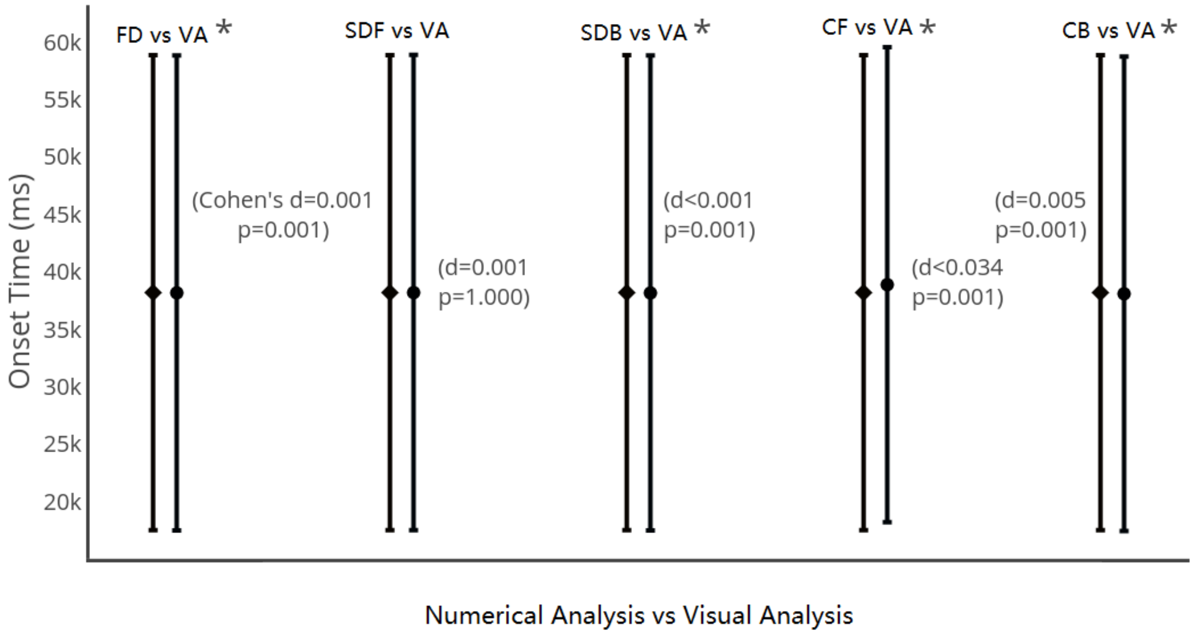

Figure 3.3 Comparison between each of numerical methods and visual analysis method. '*' indicates a statistical difference. VA, visual analysis; FD, first derivative; SDF, second derivative forward; SDB, second derivative backward; CF, curvature forward; CB, curvature backward.

Kinetic Variables Analysis

Instantaneous Force

Prior to performing a three-way mixed ANOVA on instantaneous force, data screening found seven outliers. In order to conduct the ANOVA properly, these outliers were removed and examined separately. The three-way mixed ANOVA showed statistical significance for the main effects of the analysis method ($F_{(1.483)}$=299.931, p=0.001), time point ($F_{(1.085)}$=265.090, p=0.001), group $F_{(3)}$=5.021, p=0.003), the interaction effects of the analysis method by time phases by group ($F_{(9.135, 210.110)}$ = 3.403, p = 0.001), the analysis method by time phase ($F_{(3.045)}$=102.170, p=0.001), and the analysis method by group ($F_{(4.450,102.359)}$=4.206, p=0.002). Because of the statistical interaction effect of the analysis method by time phases by group, the post hoc examination focused on breaking down the interaction effect to identify differences in the analysis methods over the four time points within each group. Scheffe adjustment was used to produce a new critical $F_{(9.135,\ 210.11)} = 17.38$. The post hoc analysis showed that the first derivative and the second derivative forward exhibited no statistical differences from the visual method in their kinetic trend over all the four time points within each group (First derivative, F test statistics ranged from 0.004 to 16.414; Second derivative forward, F test statistics ranged from 0.001 to 10.527) (Figure 3.3-6). Cohen’s d was also calculated to compare the first derivative and second derivative forward in the magnitude of practical difference from the visual method (Figure 3.3-6). The second derivative forward analysis had smaller effect size compared to the first derivative analysis in all groups except for the CM group, in which the first derivative showed Cohen’s d of 0 at each time point.

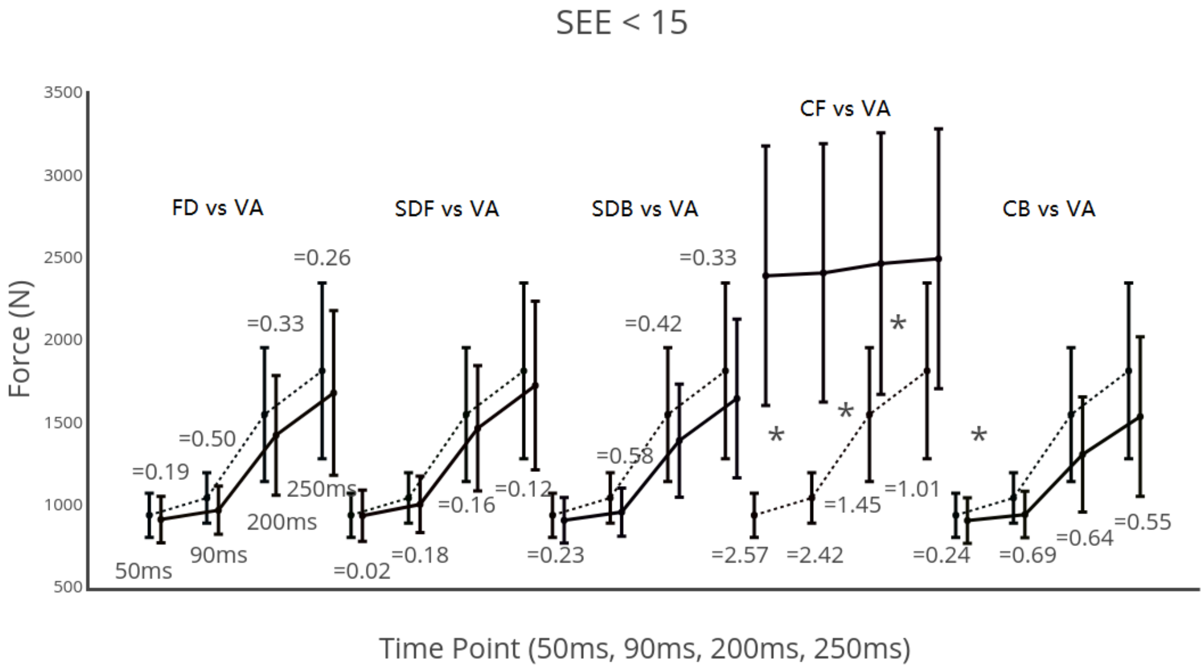

Figure 3.4 Force comparison between numerical methods and visual analysis method for SEE<15. ‘*’ indicates the statistical difference from visual analysis in the trend of two adjacent time points ($p<0.05$). ‘= (number)’ is the Cohen’s d value of each time point. VA, visual analysis; FD, first derivative; SDF, second derivative forward; SDB, second derivative backward; CF, curvature forward; CB, curvature backward.

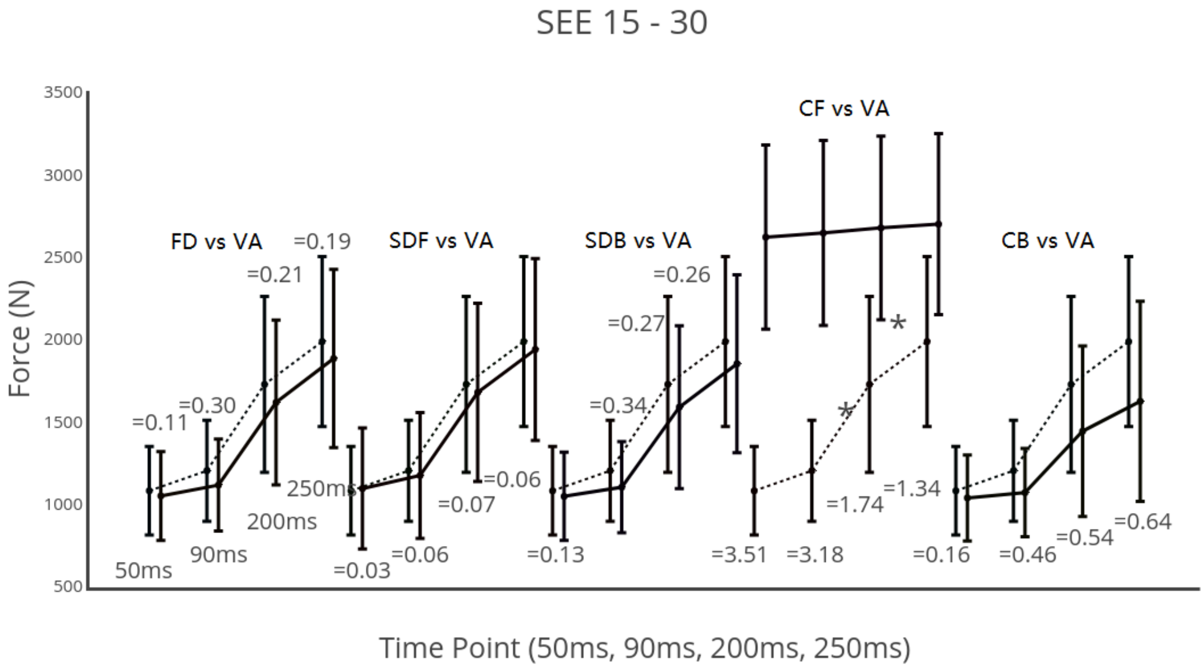

Figure 3.5 Force comparison between numerical methods and visual analysis method for SEE 15-30. ‘*’ indicates the statistical difference from visual analysis in the trend of two adjacent time points ($p<0.05$). ‘= (number)’ is the Cohen’s d value of each time point. VA, visual analysis; FD, first derivative; SDF, second derivative forward; SDB, second derivative backward; CF, curvature forward; CB, curvature backward.

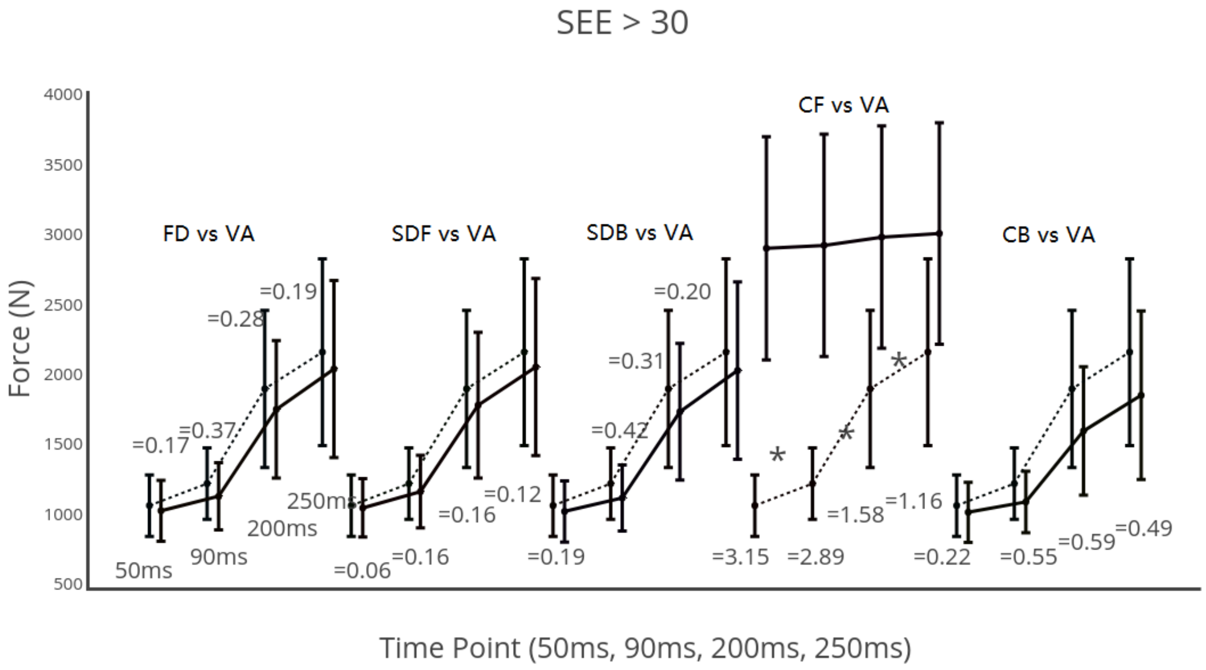

Figure 3.6 Force comparison between numerical methods and visual analysis method for SEE>30. ‘*’ indicates the statistical difference from visual detection in the trend of two adjacent time points ($p<0.05$). ‘= (number)’ is the Cohen’s d value of each time point. VA, visual analysis; FD, first derivative; SDF, second derivative forward; SDB, second derivative backward; CF, curvature forward; CB, curvature backward.

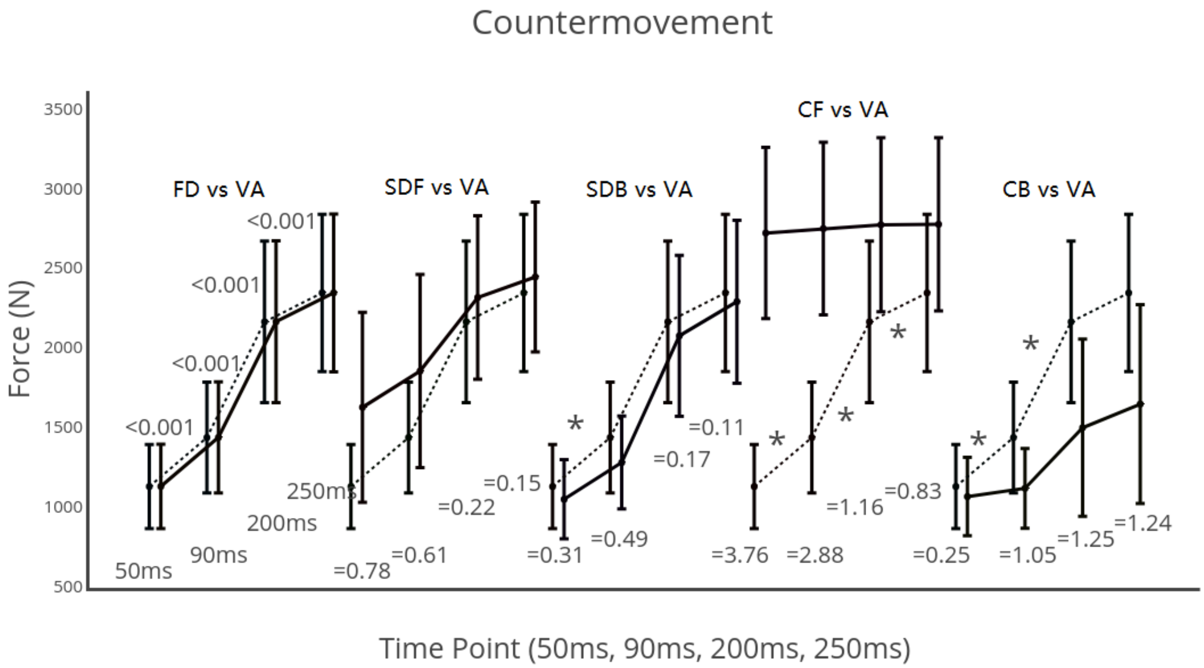

Figure 3.7 Force comparison between numerical methods and visual analysis method for Countermovement. '*' indicates the statistical difference from visual analysis in the trend of two adjacent time points ($p<0.05$). '= (number)' is the Cohen's d value of each time point. VA, visual analysis; FD, first derivative; SDF, second derivative forward; SDB, second derivative backward; CF, curvature forward; CB, curvature backward.

Rate of Force Development

Nine outliers were found for the RFD analysis and excluded prior to the further analysis. The three-way mixed ANOVA showed statistical significance for all effects after Greenhouse-Geisser adjustment for sphericity (Method, $F_{(2.395)}$=109.867, p<0.001; Method by Group, $F_{(7.185,106.456)}$=13.044, p<0.001; Time point, $F_{(1.199)}$=136.206, p<0.001; Time point by Group, $F_{(3.596, 80.312)}$=2.794, p=0.037; Method by Time point, $F_{(3.332)}$=39.296, p<0.001; Method by Time point by Group, $F_{(9.995, 223.219)}$=8.790, p<0.001). Thus, post hoc interaction contrasts of the highest order interaction were performed. After the Scheffe adjustment (Critical $F_{(9.995, 223.219)}$=19.21), the results indicated only the curvature forward and backward methods showed statistically different (F test statistic larger than 19.21) trends from the visual analysis method. Between the curvature forward method and the visual analysis method, the differences were observed over the period of 50 to 90ms in the >30 (F = 37.415>19.21), and CM (F = 32.833>19.21) groups and the period of 90 to 200ms in the <15 (F = 33.694) and 15-30 (F = 35.410) groups. Between the curvature backward method and visual analysis method, the difference was observed over the period of 50 to 90ms in the CM group (F = 20.264) (Figure 2.5.1-4). Cohen's d indicated first derivative analysis more consistently had a consistent small magnitude of difference across all time points (<0.001) from the visual analysis in the countermovement group (Figure 3.7-10) while the other methods showed more inconsistent and larger differences. In addition, the second derivative forward method showed the smallest magnitude of difference over all the time points from the visual analysis compared to the other methods except in the countermovement group. (Figure 3.7-9)

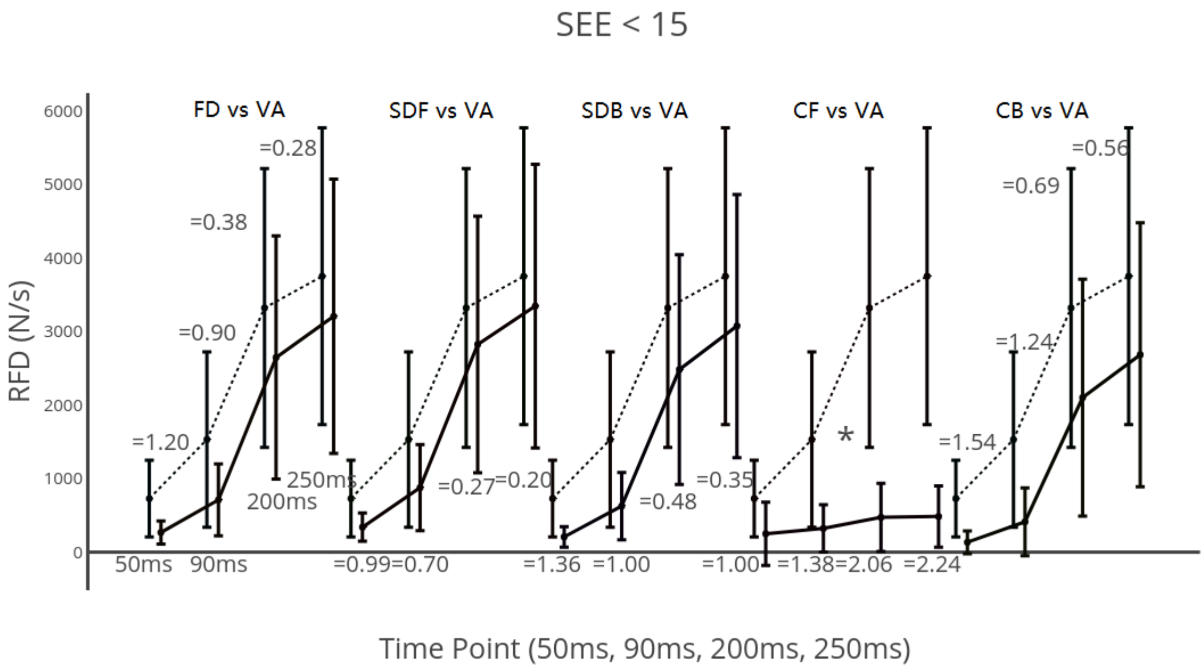

Figure 3.8 RFD comparison between numerical methods and visual analysis method for SEE<15. ‘*’ indicates the statistical difference from visual analysis over the successive instantaneous forces from two time points ($p<0.05$). ‘= (number)’ is the Cohen’s d value of each pair of strip. VA, visual analysis; FD, first derivative; SDF, second derivative forward; SDB, second derivative backward; CF, curvature forward; CB, curvature backward.

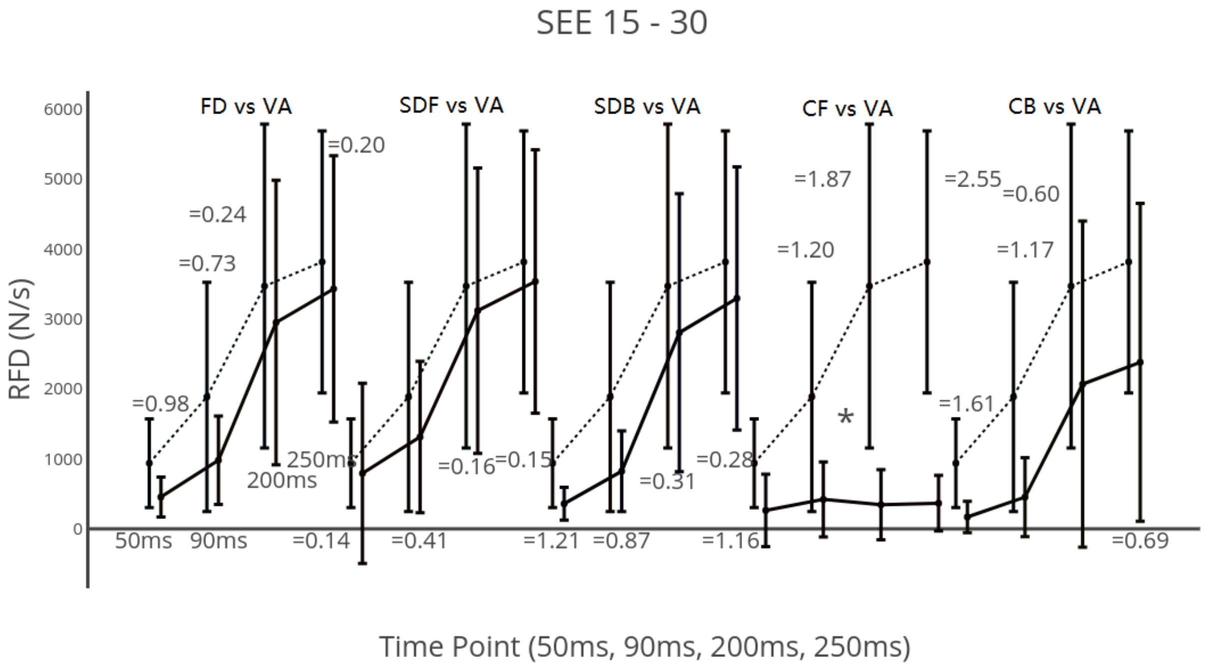

Figure 3.9 RFD comparison between numerical methods and visual analysis method for SEE15-30. ‘*’ indicates the statistical difference from visual analysis over the successive instantaneous forces from two time points ($p<0.05$). ‘= (number)’ is the Cohen’s d value of each pair of strip. VA, visual analysis; FD, first derivative; SDF, second derivative forward; SDB, second derivative backward; CF, curvature forward; CB, curvature backward.

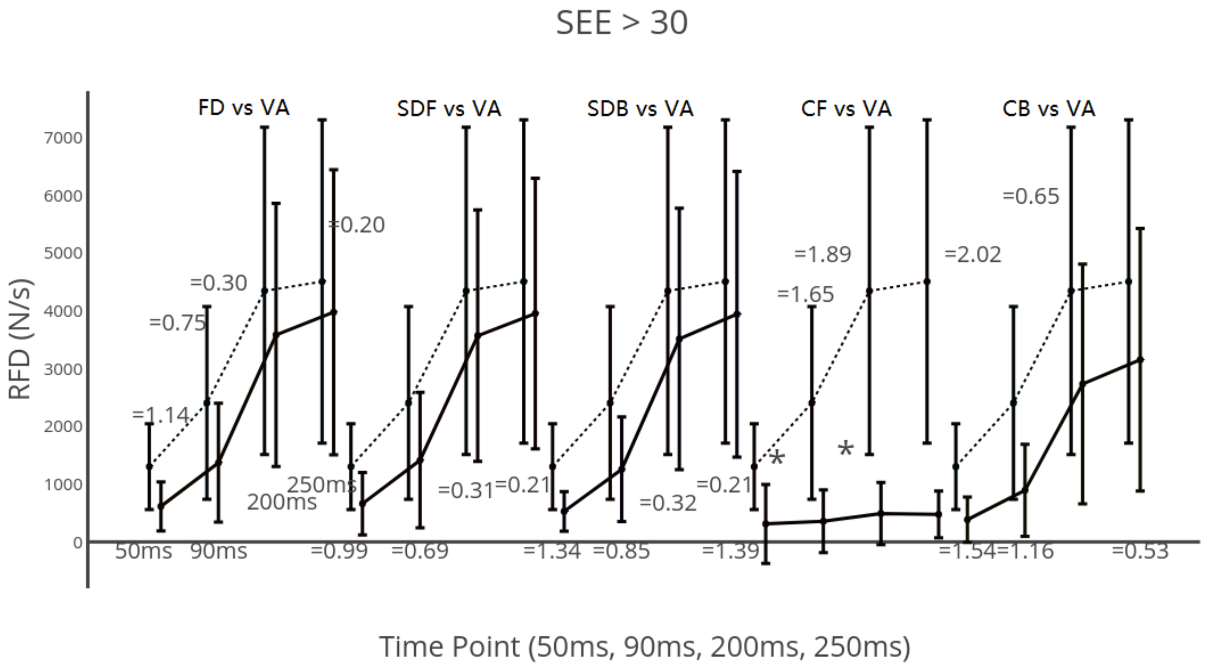

Figure 3.10 RFD comparison between numerical methods and visual analysis method for SEE>30. ‘*’ indicates the statistical difference from visual analysis over the successive instantaneous forces from two time points ($p<0.05$). ‘= (number)’ is the Cohen’s d value of each pair of strip. VA, visual analysis; FD, first derivative; SDF, second derivative forward; SDB, second derivative backward; CF, curvature forward; CB, curvature backward.

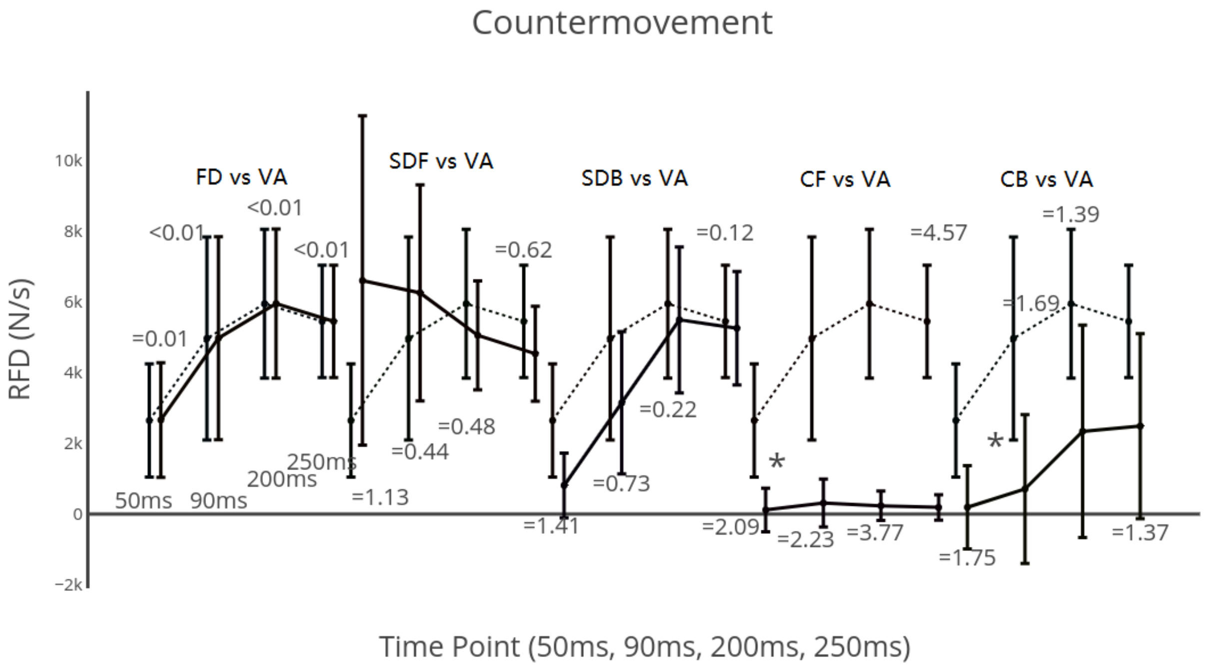

Figure 3.11 RFD comparison between numerical methods and visual analysis method for Countermovement. ‘*’ indicates the statistical difference from visual analysis over the successive instantaneous forces from two time points ($p<0.05$). ‘= (number)’ is the Cohen’s d value of each pair of strip. VA, visual analysis; FD, first derivative; SDF, second derivative forward; SDB, second derivative backward; CF, curvature forward; CB, curvature backward.

Outlier Analysis

Due to the assumptions of the ANOVAs, several scores were identified as outliers and thus the subjects to whom the outliers belonged to were excluded from the analysis. They are considered here separately from the ANOVAs as they might offer unique insight into differences between the examined methods. It is important to emphasize that an outlier may be due to inherent error in an analysis method and/or an extreme performance score. In the present study, all outliers were identified within each cell of the ANOVAs.

Instantaneous Force

Examining across all the outliers, the authors noted the following trends. 1) Curvature forward produced values greater than those by visual analysis often by more than 1000N and regardless of the baseline condition. In fact, the mean difference (standard deviation) at the four time points between visual analysis and curvature forward ignoring the baseline condition ranged from 1081.58 (± 1059.95) to 2703.76 (± 943.39) N. The only exception to this was observed at 250ms under the CM condition. 2) First derivative appeared to produce the smallest difference from visual analysis with the mean difference (standard deviation) ranging from -38.07 (± 34.36) to -94.31 (± 108.00) N. The negative sign indicates the overall trend of underestimation. From examination alone, it is difficult to determine which of the remaining methods performed more similarly than the others. However, it appeared to us that the second derivative methods performed more similarly to visual analysis than curvature backward (mean difference ± standard deviation: second derivative forward, 1.08 ± 210.56 to 386.95 ± 531.49 N; second derivative backward, -91.35 ± 58.61 to -220.48 ± 153.41 N; curvature backward, -86.33 ± 52.26 to -614.15 ± 880.33 N). It is difficult to determine if the baseline condition had any effects as there were only two or less outlier subjects per condition.

Table 3.2 Outliers for Instantaneous Force (N)

SEE<15												
	50ms						90ms					
Outlier subject	VA	FD	SDF	SDB	CF	CB	VA	FD	SDF	SDB	CF	CB
38	1712* (3.15)	1712* (3.14)	1729 (2.23)	1682* (3.18)	4006 (1.71)	1562* (2.98)	2147* (3.35)	2147* (3.42)	2170* (2.58)	2100* (3.50)	3972 (1.67)	1565* (2.79)
70	1324 (1.45)	1304 (1.41)	1948* (2.92)	1236 (1.22)	3571 (1.21)	1200 (1.22)	1584 (1.51)	1547 (1.55)	2257* (2.79)	1422 (1.28)	3615 (1.25)	1305 (1.54)
	200ms						250ms					
38	3198* (2.71)	3198* (2.92)	3214 (2.55)	3465* (3.04)	3966 (1.57)	2487 (2.40)	3501 (2.33)	3501 (2.51)	3508 (2.37)	3485* (2.61)	4004 (1.60)	2959 (2.20)
70	2452 (1.38)	2408 (1.51)	3015 (2.23)	2257 (1.36)	3766 (1.34)	2093 (1.53)	2871 (1.39)	2837 (1.52)	3090 (1.76)	2694 (1.40)	3757 (1.31)	2505 (1.44)
SEE 15-30												
	50ms						90ms					
Outlier subject	VA	FD	SDF	SDB	CF	CB	VA	FD	SDF	SDB	CF	CB
112	1541 (1.29)	1465 (1.18)	2462* (2.62)	1381 (0.97)	3776 (1.49)	1459 (1.23)	2039 (1.83)	1919 (1.95)	2948* (2.83)	1696 (1.60)	3845 (1.49)	1906 (2.25)
116	1782 (2.05)	1715 (1.99)	1788 (1.22)	1682 (1.97)	4230 (2.15)	1691 (2.00)	2211 (2.25)	1977 (2.11)	2227 (1.58)	1820 (1.98)	4407 (2.29)	1679 (1.58)
	200ms						250ms					
112	3178 (1.73)	3148 (1.89)	3027 (1.58)	3045 (1.89)	3800 (1.39)	3144* (2.59)	3077 (1.30)	3113 (1.43)	3262 (1.51)	3172 (1.56)	3774 (1.36)	3117 (2.13)
116	3742 (2.49)	3560 (2.47)	3753 (2.56)	3374 (2.37)	4477 (2.34)	1667 (0.21)	4101* (2.74)	4301* (2.66)	4103* (2.61)	3901 (2.55)	4439 (2.33)	1679 (-0.03)

Asterisks indicate that the values were identified as outliers. The values in parentheses are the corresponding z scores used to identify outliers.

Table 3.3 Outlier for Instantaneous Force (N) (Continued)

SEE >30												
Outlier	50ms						90ms					
subject	VA	FD	SDF	SDB	CF	CB	VA	FD	SDF	SDB	CF	CB
	2264*	2254*	2257*	2250*	5011	2252*	2281	2278*	2279	2277*	5008	2277*
81	(2.78)	(2.86)	(2.89)	(2.86)	(1.47)	(2.92)	(2.33)	(2.65)	(2.55)	(2.66)	(1.47)	(2.86)
	2014	1936	1937	1936	6811*	1893	2315	2067	2073	2067	6777*	1936
149	(2.15)	(2.05)	(2.06)	(2.06)	(2.93)	(1.99)	(2.41)	(2.12)	(2.04)	(2.14)	(2.92)	(1.96)
	200ms						250ms					
	2342	2339	2339	2338	4953	2338	2383	2377	2379	2375	4943	2376
81	(0.50)	(0.82)	(0.75)	(0.84)	(1.35)	(1.21)	(0.13)	(0.31)	(0.29)	(0.32)	(1.33)	(0.62)
	3674	3301	3313	3301	7031*	2818	4422*	3979	3994	3979	7018*	3424
149	(2.50)	(2.45)	(2.34)	(2.47)	(3.02)	(2.11)	(2.64)	(2.47)	(2.47)	(2.47)	(3.02)	(2.17)
CM												
Outlier	50ms						90ms					
subject	VA	FD	SDF	SDB	CF	CB	VA	FD	SDF	SDB	CF	CB
	1685	1673	2909	1516	3844	1661	2352	2334	3303	2004	3947	2315*
7	(1.86)	(1.82)	(1.88)	(1.69)	(1.84)	(2.08)	(2.20)	(2.16)	(2.04)	(2.11)	(1.93)	(3.14)
	200ms						250ms					
	3547	3541	3798	3411	3963	3534*	3768	3765	3794	3707	3759	3763*
7	(2.26)	(2.25)	(2.35)	(2.21)	(1.90)	(2.74)	(2.35)	(2.34)	(2.34)	(2.28)	(1.63)	(2.61)

Asterisks indicate that the values were identified as outliers. The values in parentheses are the corresponding z scores used to identify outliers.

Rate of Force Development

Similarly to the instantaneous force outliers, the two curvature method appeared to have the larger difference from visual analysis than the first derivative or second derivative methods with the mean difference ranging from -862.14 (± 3216.26) to -5926.47 (± 3503.84) N/s when ignoring the baseline condition. Furthermore, another similar trend was observed between the first derivative and second derivative methods in that the first derivative method in general appeared to produce smaller differences from visual analysis than the two second derivative methods (-121.79 ± 247.72 to -659.46 ± 814.92 N/s). Between the two second derivative methods, differences appeared similar (forward: -44.06 to 3801.33 N/s vs. backward: -474.89 to -2170.67 N/s). Again, given the number of outlier subjects per condition, it is difficult to determine relationships between the baseline condition and outliers.

Table 3.4 Outlier for RFD (N/s)

SEE<15

Outlier subject	50ms VA	FD	SDF	SDB	CF	CB	90ms VA	FD	SDF	SDB	CF	CB
38	2981	2981*	3311	2369*	1149	390	6487*	6487*	6744	5958*	252	254
	(2.53)	(3.37)	(1.18)	(4.01)	(0.27)	(0.96)	(2.74)	(3.46)	(2.41)	(3.76)	(-0.30)	(-0.43)
53	551	319	600	252	7623*	51	1390	706	1506	539	4786*	92
	(-0.52)	(-0.29)	(-0.25)	(-0.20)	(4.08)	(-0.48)	(-0.36)	(-0.35)	(-0.10)	(-0.37)	(4.02)	(-0.70)
69	1614	926	4483	405	104	876*	2855	2239	4222	1604	98	2186*
	(0.81)	(0.55)	(1.80)	(0.11)	(-0.35)	(3.02)	(0.54)	(0.66)	(1.20)	(0.44)	(-0.45)	(2.82)
70	2530	2072	7588*	669	1099	166	4291	3886	7648*	2437	1102	1073
	(1.96)	(2.12)	(3.43)	(0.63)	(0.24)	(-1.41)	(1.41)	(1.74)	(2.84)	(1.08)	(0.51)	(0.95)

Outlier subject	200ms VA	FD	SDF	SDB	CF	CB	250ms VA	FD	SDF	SDB	CF	CB
38	8172	8172	8253	8008*	84	4723	7751	7751	7779	7683	221	5665
	(2.13)	(2.48)	(2.27)	(2.62)	(-0.83)	(1.42)	(1.76)	(2.02)	(1.99)	(2.14)	(-0.67)	(1.47)
53	1992	1879	2020	1851	1874	50	2835	2121	2950	1940	1768	53
	(-0.78)	(-0.58)	(-0.58)	(-0.53)	(2.38)	(-1.31)	(-0.56)	(-0.68)	(-0.33)	(-0.72)	(2.50)	(-1.45)
69	3335	3193	3129	3005	203	3180	3048	2986	2551	2896	249	2979
	(-0.15)	(0.05)	(-0.07)	(0.06)	(-0.62)	(0.51)	(-0.46)	(-0.26)	(-0.53)	(-0.24)	(-0.61)	(0.07)
70	6269	6052	7229	5272	1252	4422	6692	6561	6084	5963	966	5187
	(1.24)	(1.45)	(1.80)	(1.22)	(1.26)	(1.24)	(1.26)	(1.45)	(1.18)	(1.28)	(0.86)	(1.22)

SEE15-30

Outlier subject	50ms VA	FD	SDF	SDB	CF	CB	90ms VA	FD	SDF	SDB	CF	CB
112	3827*	2350*	12730*	616	-54	2209*	7660	6348*	12472	3840*	736	6199*
	(2.91)	(3.44)	(3.83)	(1.08)	(-0.64)	(3.83)	(2.41)	(3.48)	(3.62)	(3.20)	(0.25)	(3.91)
116	2287	1062	2387	313	1364	-81	6038	3505	6205	1712	2731*	-178
	(1.23)	(0.94	(0.31)	(-0.24)	(1.91)	(-0.67)	(1.67)	(1.49)	(1.43)	(0.79)	(3.00)	(-0.63)

Outlier subject	200ms VA	FD	SDF	SDB	CF	CB	250ms VA	FD	SDF	SDB	CF	CB
112	9144	9001	6007	8472	108	8979	6910	7059	5746	7285	-16	7076
	(1.72)	(1.99)	(0.92)	(1.98)	(-0.52)	(2.43)	(1.15)	(1.33)	(0.78)	(1.51)	(-0.95)	(1.86)
116	10372	9489	10420*	8539	1579	-137	9733	9476	9739	8939	1110	-62
	(2.14)	(2.16)	(2.63)	(2.01)	(2.15)	(-0.89)	(2.38)	(2.35)	(2.52)	(2.22)	(1.72)	(-1.04)

Asterisks indicate that the values were identified as outliers. The values in parentheses are the corresponding z scores used to identify outliers.

Table 3.5 Outlier for RFD (N/s) (Continued)

SEE>30												
Outlier subject	50ms						90ms					
	VA	FD	SDF	SDB	CF	CB	VA	FD	SDF	SDB	CF	CB
151	3136 (2.10)	2924* (3.32)	6290* (3.92)	2597 (3.44)	1769 (1.87)	2814* (3.47)	4577 (1.22)	4394 (2.38)	8783* (3.49)	4134 (2.50)	1386 (1.69)	4305* (2.98)
	200ms						250ms					
151	8258 (1.29)	8120 (1.77)	10415 (2.49)	7912 (1.73)	625 (0.24)	8051 (2.15)	9100 (1.50)	9028 (1.81)	9924 (2.15)	8911 (1.78)	683 (0.50)	8990 (2.15)
CM												
Outlier subject	50ms						90ms					
	VA	FD	SDF	SDB	CF	CB	VA	FD	SDF	SDB	CF	CB
5	898 (1.08)	898 (-1.08)	4333 (-0.53)	-458 (-1.34)	743 (0.85)	-476 (-0.57)	2427 (-0.89)	2427 (-0.89)	3747 (-0.82)	-35 (-1.47)	1847 (1.76)	-476 (-0.57)
7	4882 (1.34)	4644 (1.19)	15195 (1.71)	1267 (0.54)	1149 (1.48)	4411* (2.74)	10122 (1.66)	9921 (1.61)	12818 (1.92)	6122 (1.39)	1781 (1.67)	9718* (3.02)
	200ms						250ms					
5	3251 (-1.20)	3251 (-1.20)	5207 (-0.01)	2151 (-1.46)	1383 (2.16)	-328 (-0.85)	3998 (-0.89)	3998 (-0.89)	5147 (0.35)	2465 (-1.53)	1373* (2.60)	-25 (-0.92)
7	10532 (1.92)	10500 (1.91)	8247 (1.86)	9794 (1.83)	878 (1.13)	10468 (2.28)	9308 (2.11)	9299 (2.10)	6580 (1.41)	9019 (1.99)	-114 (-0.79)	9289 (2.21)

Asterisks indicate that the values were identified as outliers. The values in parentheses are the corresponding z scores used to identify outliers.

DISCUSSION

In the present study numerical methods were applied to the analysis of the isometric mid-thigh pull force-time curves and compare the results to those of visual analysis for compatibility. Four different conditions were considered based on the characteristics of the baseline prior to the onset of a pull. The primary findings of the study were 1) despite the trivial effect sizes, differences in onset time may hold practical significance, and 2) the first derivative and the second derivative forward used together can provide comparable scores of the kinetic variables to the visual analysis method.

Onset Time

The results suggest that the onset time appears similar between visual analysis method and the numerical methods. This is based on the fact that all effect sizes were trivial ($d < 0.1$) despite the statistical differences. At the same time, it is important to note that Cohen's d is a standardized difference and thus when data have similar means but large standard deviations (Figure 2.3), a practically meaningful difference can be masked. Because it is common to examine kinetics within a small time window such as 50 to 250ms in the IMTP test, a mean difference of 100ms, for example, between two methods can lead to a practically meaningful difference in time-dependent variables but appear as a trivial difference in onset time when divided by a pooled standard deviation of 25000ms. In addition, the observed differences between the visual analysis method and each of the numerical methods appear independent of the undulation and the presence of a countermovement in the baseline as suggested by the lack of statistical significance for the main effect of group and the two-way interaction effect.

Kinetic Variables

Another important finding in this study was that differences between the methods in the kinetic variables measured within certain time windows appeared to be related to the condition of baseline. The relationship with the baseline condition was observed despite the trivial effect sizes for the onset time. Specifically, with the presence of a countermovement in a baseline, the first derivative method produced the smallest difference without a statistical difference from the visual analysis method for both the instantaneous force and RFD. In fact, it appears that first derivative is the only method that can function comparably to visual analysis.

Effectiveness of first derivative in onset detection appears to be in agreement with what Tillin et al. recommend (21). For baseline with SEE ‘<15’, ’15-30’ and ‘>30’, the second derivative forward method produced the smallest difference without statistical significance from the visual analysis method, again, for both the instantaneous force and RFD. It may also be worth noting that an increase in baseline undulation measured by SEE does not appear to lead to a linear increase in the difference between second derivative forward and visual analysis based on effect size. These observations suggest that first derivative and second derivative forward are likely two preferred methods of all the numerical methods examined and should be used under different baseline conditions. With a countermovement, first derivative method appears to perform superiorly to any other methods while in all other baseline conditions, second derivative forward may be a preferred method.

Outliers

First derivative method appears to resemble visual analysis in outliers more than the other methods for both instantaneous force and RFD. This is somewhat surprising given the results of the ANOVAs, which appear to suggest second derivative forward as the method most similar to visual analysis. While it is difficult to make any useful inferences as to the cause of this observation, the observation can be interpreted in such that first derivative may have the least probability to mal-function of all the methods. It is also important to note that second derivative forward still appears to resemble visual analysis more than the two curvature methods.

In conclusion, the numerical methods can identify onset times similar to the visual analysis. However, despite the similar onset times, resulting values of the kinetic variables showed greater variance between many of the numerical methods and the visual analysis method than the authors expected. The first derivative and second derivative forward methods appear to have the smallest difference in the kinetic variables from the visual analysis method with the presence of countermovement and the lack of it, respectively. The outlier analysis appears to indicate that first derivative may be the most consistent method of all in terms of similarity to visual analysis. The two curvature methods are not recommended for kinetic analysis of the isometric mid-thigh pull test.

PRACTICAL APPLICATIONS

The findings of this study suggest that sport scientists could use the first derivative and second derivative forward methods, interchangeably with visual analysis method, depending on the presence of a countermovement. It is a plausible idea to design an algorithm that detects a countermovement and subsequently chooses the first derivative or the second derivative forward method. However, based on the outliers, it is strongly suggested that analysis results using the suggested method are inspected by a sport scientist for any erroneous values prior to further use. A visual analysis method would still be necessary throughout the process for entry-level practitioner, but the combined method could facilitate the understanding of identifying the onset time.

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CHAPTER 4

DIFFERENCES OF ONSET MOVEMENT IDENTIFICATION ANALYSES USED IN ISOMETRIC MID-THIGH PULL TEST

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Brief running head: Onset movement analysis

Abstract

The objective of the study was to examine methods of onset identification for the isometric mid-thigh pull test. Methods using differential calculus principle (CA) and standard deviation threshold (SA) were compared to visual analysis (VA). Onset time, instantaneous force, and rate of force development were examined under four baseline conditions (baseline undulation by standard error of estimate: SEE<15N, SEE 15-30N, SEE>30N and an observed countermovement). A statistical difference ($p<0.05$) was observed between SA and CA, SA and VA for onset time in SEE>30. For instantaneous force, there were statistical differences ($p<0.05$) at time 50ms and 90ms in SEE>30 between SA and CA and SA and VA, respectively. A statistical difference was also found between the methods at 90ms and 200ms with the countermovement. For rate of force development, there were statistical differences ($p<0.05$) over 200ms and 250ms in SEE>30 between SA and MA and SA and VA, respectively. Moreover, statistical differences were observed during periods less than 200ms with countermovement. CA appears to produce more similar results to VA than SA. However, erroneous values are still possible in both CA and SA with VA as a reference.

Key words: calculus; threshold; visual analysis; force-time curve; analysis

INTRODUCTION

The isometric mid-thigh pull (IMTP) test is commonly performed on a force plate and thus provides a variety of kinetic variables from recorded ground reaction force. Because of its isometric nature, the test is expected to have less metabolic demands (13) than other tests such as squat 1RM. Also, the isometric nature is expected to render the test less fatiguing due to the minimal amount of eccentric action and thus has a smaller probability of muscle damage (5). Furthermore, variables obtained from the test have been reported to correlate with other performance tests (1, 14). The efficient safe test plus sufficient kinetic variables output for analysis-appear to make the test a viable option (1, 6, 7, 14) for athlete monitoring.

Because all variables come from ground reaction force, the test requires use of a computer to digitally sample an analogue signal of ground reaction force and calculate various variables. Common variables appear to be peak force, single point force value (i.e. instantaneous force) at various time points, and rate of force development over various time periods from the onset of an IMTP (1, 7, 14). As one might notice, most of the aforementioned variables rely on the identification of the onset of a pull. In the current literature, there appear to be two methods used to identify the onset in IMTP test. The more common method of the two uses simple visual examination in each force-time curve for onset detection. The other method uses a force threshold (3, 4, 9, 12). Recently, Dos'Santos et al. recommended using 5 times the standard deviation of baseline force as the onset threshold (3). The use of a threshold is purported to allow for a more objective identification of the onset and reduce data analysis time.

While the use of a threshold was reported to be sufficiently reliable (3), this method is hypothesized to rely on a level baseline with little force undulation in order to calculate an effective standard deviation. In practical settings, while attempts may be made, it is not always practical to obtain a level baseline with little undulation. Thus, it is worthwhile to examine how the threshold method as recommended by Dos'Santos performs under various baseline conditions. Moreover, our recent work on use of differential calculus principles showed some success in producing onset identification similar to the visual examination method. While there does not appear to be any evidence to suggest that the visual examination method does truly identify the onset, being able to produce similar onsets to the visual examination method can be useful in reducing training of raters and analysis time if one wishes to switch from the visual examination method to the method based on differential calculus principles.

The objective of the present study was to compare the visual examination analysis method (VA), a threshold-based analysis method (SA) such as that reported by Dos'Santos (3), and a differential calculus-based analysis method (CA) to analyze force-time curves of the IMTP test. Through this study, the authors intend to help practitioners find an analysis method suitable for their settings.

METHODS

Experimental Approach to the Problem

In order to examine how the three methods may differ, the following factors are considered as they were speculated to influence the performance of the methods: the condition of the baseline prior to the onset of a pull and time elapsed since the onset of a pull. The condition of the baseline was included as a factor because many common time-dependent kinetic variables such as force at 200ms or rate of force development (RFD) over 250ms are measured in relation to the onset of a pull. A method has significant error in the onset identification if the baseline condition is not suitable for the method. Time elapsed since the onset of a pull was considered as a factor in order to examine how differences in the onset identification can influence kinetic variables with different time periods.

To examine the two factors above, a total of 80 independent trials belonging to 80 athletes were selected from our long-term athlete monitoring archive. These 80 trials were selected such that there would be four groups of 20 subjects. These groups were created based on the two baseline characteristics. If a trial had a countermovement, the athlete of the trial was placed into the countermovement group. If a trial did not have a countermovement, the baseline was evaluated for its level of undulation. This evaluation was accomplished by first applying the best fit linear trend line through the baseline for 1.5 seconds prior to an approximated point of the onset of an isometric pull and then calculating a standard error of estimate (SEE) associated with the best fit line. The best fit linear trend line and SEE were used over a mean and standard deviation of the baseline force because the use of a mean and standard deviation would overestimate the level of undulation if the baseline had an upward or downward trend. Trials without a countermovement were then placed into the remaining three groups based on the following three levels of baseline undulation: SEE <15 N (8.10±3.38 N), SEE from 15 to 30 N (18.98±3.63 N), and SEE > 30 N (47.25±18.68 N) (Figure 4.1).

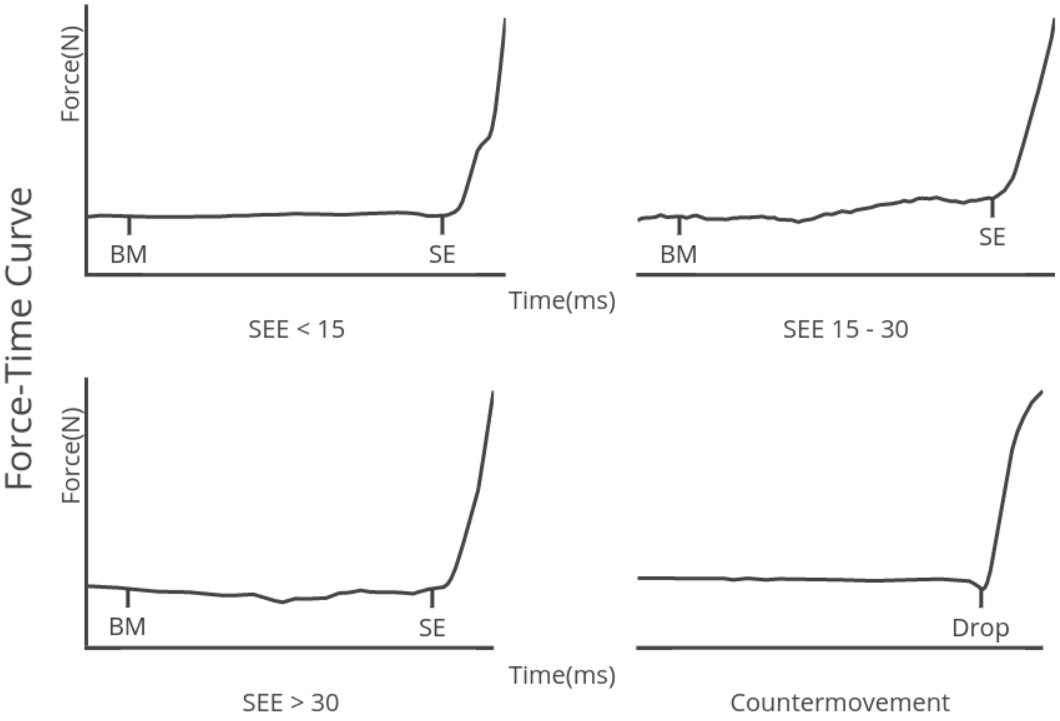

Figure 4.1 Examples of four baseline characteristics. BM: the start of the baseline measurement; SE: an approximated onset point of a pull. Time from BM to SE was 1500ms.

Subjects

Eighty independent samples (Table 3.1) were selected based on the aforementioned criteria in such a manner that there would be 20 samples for each of the four groups. Furthermore, each group included subjects from at least four sports and up to five sports. (Table 4.1). All samples were retrieved from the on-going athlete monitoring program repository in the Department of Sport and Exercise Laboratory of East Tennessee State University. The study was approved and granted a waiver for informed consent by Institutional Review Board at the university.

Table 4.1 Characteristics of subjects.

SEE	Age (yrs)	Height (cm)	Mass (kg)	Sports	Peak Force (N)
< 15	20.4±1.3	171.5±12.0	72.0±14.6	Soccer: 2 males, 3 females, Basketball: 2 males, Tennis: 3 males, 3 females, Volleyball: 3 females, Softball: 4 females	3043±865
15 – 30	20.4±1.5	174.4±8.4	78.8±15.1	Soccer: 2 males, 4 females, Basketball: 2 males, 3 females, Tennis: 2 females, Softball: 3 females, Volleyball: 4 females	3293±823
>30	20.8±1.5	176.0±7.1	74.6±6.6	Soccer: 4 males, 4 females, Volleyball: 5 females, Tennis: 5 males, Baseball: 2 males	3809±1245
Countermovement	21.1±1.6	178.4±10.7	76.7±12.0	Soccer: 5 males, 2 females, Basketball: 3 males, 2 females, Volleyball:3 females, Tennis: 3 males, 2 females	3240±566

∗Peak force was the maximal force value during the isometric mid-thigh pull.

Procedures

Testing Equipment

Data were collected as previously described (6, 7, 14) using a pair of uni-axial force plates placed side by side (Rice Lake Weighing Systems, Rice Lake, WI). Analog voltage signal from the force plates were sent to an amplifier (Temecula, California) and digitized using LabView by National Instruments (Austin, TX). The digitized data were then manipulated using a custom-made program to produce a force-time curve for further analyses.

Isometric Mid-Thigh Pull Testing Protocol

The protocol began with warm-up as described previously (6, 7, 14). Subjects were then placed inside a customized power rack in the power position with clean grip width on a pair of force plates placed side by side (1, 6). Wrist straps and tapes were used to secure the hands onto an immovable bar because grip strength is often the limiting factor in producing greater force. Subjects were instructed to exert slight pulling tension onto the bar to remove tissue slack in order to minimize a position change during an actual trial. Two warm-up trials were given at perceived 50 and 75% of maximal effort (1). In maximal trials, Subjects were told to pull 'as fast and as hard as possible' until two trials differing no more than 250N in peak force were obtained (1). However, for the sake of this study, only one trial was used as averaging multiple trials would reduce error, which was of interest in this study.

Variables

The following force-time curve variables were obtained using each analysis method: onset time, forces at 50, 90, 200, and 250ms, and RFD-over 50, 90, 200, and 250ms periods from the onset. These variables were chosen due to their speculated dependency on accuracy of a pull onset identification and their common use in the isometric mid-thigh pull literature (6, 7, 14). Onset time was defined as the beginning of an isometric mid-thigh pull on a force-time curve. This was measured as time elapsed from the point at which the computer was initiated to record incoming voltage signal from the force plates. Forces at the four different time points were defined as an instantaneous force at the respective time from the onset time. Rate of force development over the four different time periods were defined as a change in force over the respective time period divided by the time elapsed in seconds.

Force-Time Curve Analyses

Three different analysis methods were employed to analyze the same 80 trials: the VA, SA (3), and CA. For all methods, data were filtered using the 2nd order Butterworth low pass digital filter with the cutoff frequency of 10Hz to minimize electrical noise in the data.

The VA method was performed by a rater experienced in analyzing isometric mid-thigh pull force-time curves. An onset time was found for each trial by visually identifying a point at which the force-time curve continuously and rapidly arose. If there was a countermovement, the bottom of the inflection caused by the countermovement was used as the onset point. In order to standardize pixelation on a computer screen, approximately 2.5 seconds of each curve including the baseline and onset point were displayed on the same screen with no change in resolution setting. Upon identification of an onset point, the remaining variables were calculated. A custom-made computer program using LabView (ver. 2010) was used for the visual analysis method. Furthermore, filtered force-time curve data in the custom-made program were exported for the other analysis methods using MatLab (Version 2015, The MathWorks, Inc., Natick, Massachusetts) to ensure that possible differences in computer algorithm used in the analysis steps such as filtering would not cause differences in the variables between the methods. Peak force values were compared between the two software programs to ensure that identical force values were used.

The CA method was designed based on the findings of our previous work (10). Our previous work examining applications of different calculus techniques suggested that the combined use of first and second derivatives may produce results most similar to the conventional visual analysis method. Specifically, if there is a countermovement in the baseline, first derivative appears to be the most effective in identifying the onset while in trials without a countermovement, second derivative appears to be the most effective. Thus, in the present study, a computer algorithm was written to combine these two techniques in such a way that trials with a countermovement were analyzed with first derivative and the others were analyzed with second derivative.

The application of both calculus techniques began with applying first derivative to find an escalating period. The application of first derivative allowed us to identify every critical point (i.e. peak and valley in a force-time curve) and the duration between each critical point (Figure 4.2). The longest section of a force-time curve between two adjacent critical points with a positive slope of its tangent line was then marked as an escalating period (e.g. a period during which force arose rapidly).

In the application of first derivative, the very first data point during the escalating period was identified as the onset. Upon identification of the onset, the remaining variables were calculated. In the application of second derivative, a computer algorithm was written to read data points of plotted second derivative forward (i.e. chronological order) from the beginning of the escalating period. The first inflection point as a computer read forward was identified as the onset.

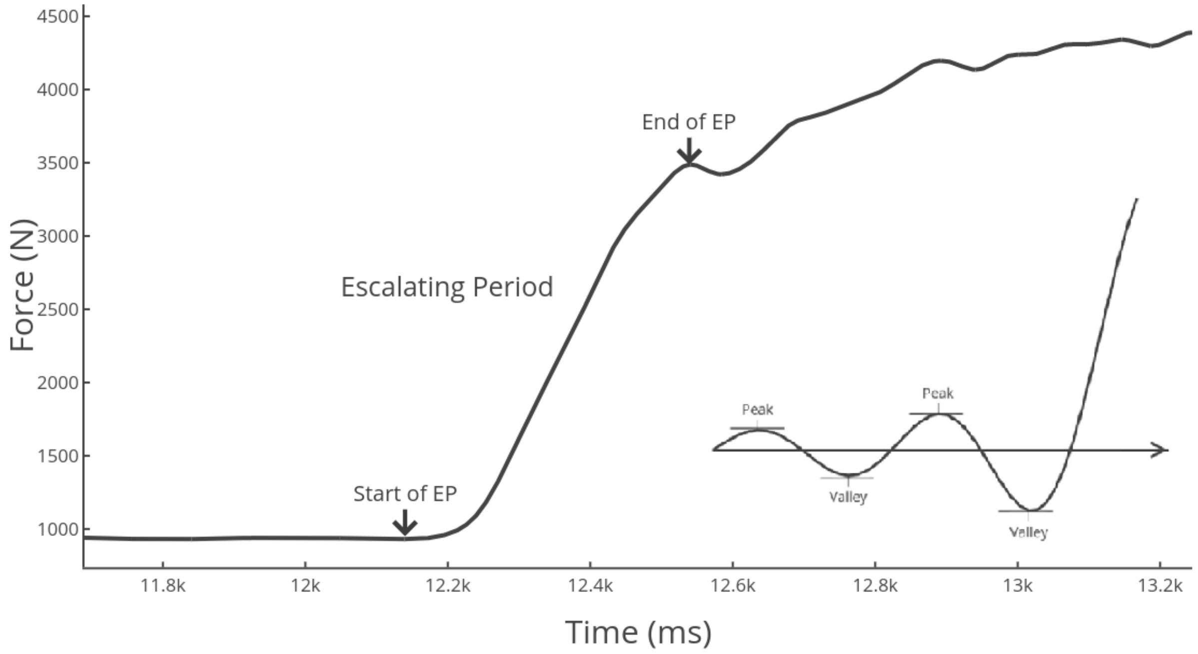

Figure 4.2 Example of a time-series curve with peaks and valleys identified using first derivative. A section between a pair of adjacent peak and valley has a set of tangent lines with the same sign (positive or negative) for the slope. The longest section with a set of positive slopes is the escalating period (i.e. from the last valley ‘Start of EP’ on to the next peak of the curve ‘End of EP’).

The SA method was designed after the method reported by Dos’Santos et al. (3). This method relies on the use of a threshold to identify the onset of a pull. Of five thresholds Dos’Santos et al. examined, they recommended the use of five times a standard deviation of the baseline force measured for at least one second prior to the instruction to begin pulling. Dos’Santos et al. controlled any movements including a countermovement during the baseline measurement; i.e. any trials with recorded force greater than 50N above or below body weight or with a countermovement were rejected. In each accepted trial, all digitized force data points during the baseline measurement were averaged and the associated standard deviation was calculated. The standard deviation was then multiplied by five and the first time the force exceeded this value plus body weight was identified as the onset of a pull.

In the present study, the same threshold of five times a standard deviation was used. However, an athlete’s movement was not controlled as done by Dos’Santos et al. because one of the objectives of the study was to examine the performance of the standard-deviation based threshold under different baseline conditions. Furthermore, a computer algorithm was written to apply the threshold. To apply, the first data point in the escalating period was approximated as the onset. In order to further reduce the probability that the one-second period immediately before the approximated onset included part of a pull, the one-second period to calculate mean body weight and the associated standard deviation was set additional 500ms before the approximated onset. Upon the calculation of the mean and standard deviation, the first data point exceeding the threshold (i.e. the mean force + 5 × standard deviation) was identified as the actual onset.

Statistical Analysis

Data were first screened for outliers and normal distribution. Outliers were checked for within each group using 2.58 multiplied by the standard deviation. For the onset time analysis, a two-way mixed analysis of variance (ANOVA) was used to test for an interaction effect of the method by baseline condition and the main effect of each. For instantaneous force and rate of force development, two three-way mixed ANOVAs were applied to examine for interaction and main effects of the method, baseline condition, and time elapsed since onset. If a statistical interaction effect was found, Scheffe adjustment was used post hoc to account for an increased type I error rate associated with experimental-wise error. If a main effect was found to be statistical, a post hoc pairwise comparison with an appropriate adjustment for an increased type I error rate. Cohen's d (a mean difference divided by a pooled standard deviation) was calculated when appropriate in order to evaluate a magnitude of difference in practical settings. The following rating scale was used: trivial = <0.1, small = 0.2-0.6, moderate = 0.6-1.2, large = 1.2-2.0, and very large = 2.0-4.0 (2, 8).

RESULTS

Onset Time Analysis

The two-way mixed ANOVA with the Greenhouse-Geisser adjustment indicated a statistical interaction effect between the method and the baseline condition ($F_{(5.320,\ 134.768)}=2.917$, $p=0.014$). However, post-hoc interaction contrasts failed to find any statistical contrasts after Scheffe adjustment with the adjusted critical F = 12.139. All calculated Cohen's ds between any pairs of methods were less than 0.001 (Figure 4.3). The main effect of method was statistical ($F_{(1.773,\ 134.768)} = 70.122$, $p < 0.001$) while that of baseline condition was not ($F_{(3,\ 76)} = 1.493$, $p = 0.223$). Post hoc pairwise comparisons with Bonferroni adjustment on the effect of method indicated that all methods were different from each other (VA vs. CA with $p = 0.045$, VA vs. SA with $p < 0.001$, and CA vs. SA with $p < 0.001$). Cohen's d corresponding to each pairwise comparisons ranged from 0.001 to 0.003.

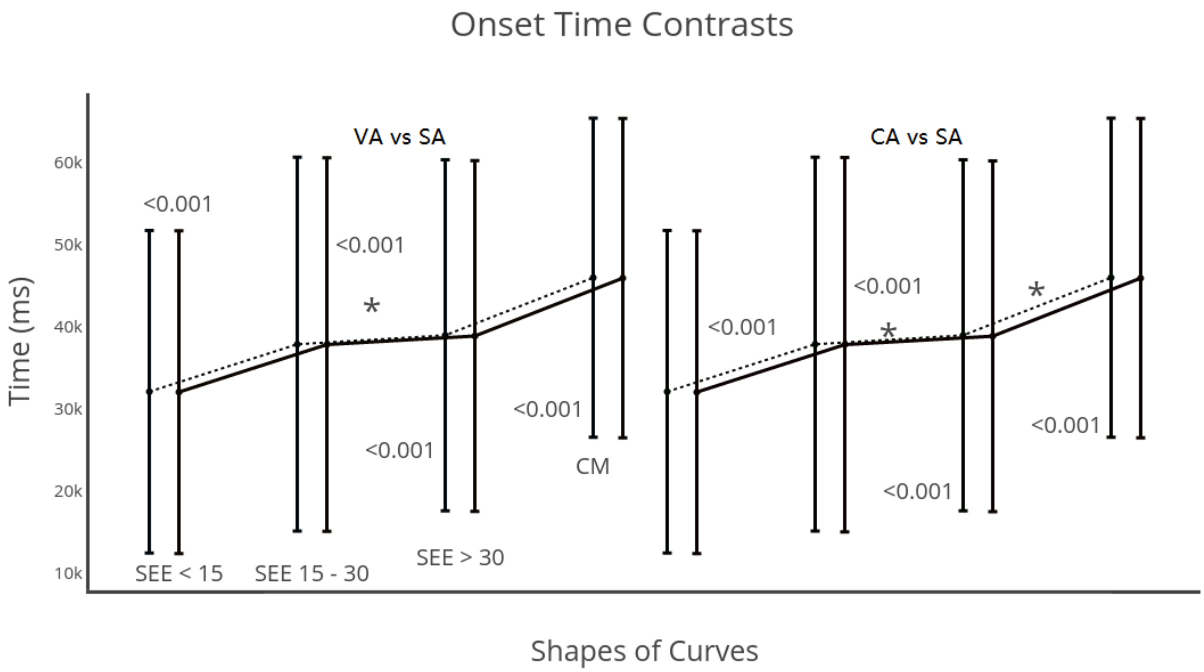

Figure 4.3 The onset time contrasts between threshold-based analysis ‘dotted line’ (SA) and other methods. (VA, visual analysis; CA, calculus analysis) Mark ‘*’ indicated the interaction effect between different curves by the analysis methods ($p<0.05$). The number over the strip of each column showed the cohen’s d between two methods.

Kinetic Variables Analysis

Instantaneous Force

After six outliers were removed, the three-way mixed ANOVA with Greenhouse-Geisser adjustment indicated a statistical three-way interaction effect ($F_{(6.047,\ 141.106)} = 7.575$, $p < 0.001$). Thus, post hoc interaction contrasts with Scheffe adjustment (adjusted critical F = 13.082) were conducted at each level of Group. The contrasts then showed the lack of statistical contrasts between VA and CA between any two adjacent time points while VA and SA, CA and SA were both found to have statistical interaction either between 50 and 90ms time points or between 90 and 200ms time points under almost all baseline conditions (Figure 3.2.1-3.2.4).

Simple comparisons between two methods were then conducted at each level of baseline condition at each time point. The results revealed the lack of statistical differences between VA and CA at every time point at each level of baseline condition. However, SA was statistically different from either or both of the other two methods. In SEE <15, SA differed from VA at 200ms ($F_{(1, 70)}$ = 15.689) and from CA at 200 and 250ms ($F_{(1, 70)}$ = 19.989 and 20.885, respectively). In SEE 15-30, SA differed from VA at all time points ($F_{(1,70)}$ = 14.548-25.751) and from CA at all but 50ms ($F_{(1, 70)}$ = 13.173-23.743). In SEE >30, SA differed from VA and CA at all time points ($F_{(1,70)}$ = 25.878-60.722). In CM, SA differed from VA and CA at all time points but 250ms ($F_{(1, 70)}$ = 13.359-137.619).

Cohen’s d was calculated in association with the simple comparisons between two methods at each level of time elapsed at each level of baseline condition (Figures 4.4-7). Cohen’s d values ranged from 0.01 to 0.18 when comparing VA and CA while they ranged from 0.01 to 0.74 when comparing VA or CA to SA. It appeared that higher Cohen’s d values were observed more frequently at the SEE <15 level.

In order to examine the effect of baseline condition, interaction contrasts were performed between two baseline conditions between two methods at each time point. The results revealed statistical contrasts between CM and each of the other conditions between CA and DA at 50ms ($F_{(1, 70)}$ = 22.949-25.902)). Simple comparisons between two conditions for each method at each time point were not performed because the differences could have reflected both effects of baseline condition and qualities of athletes (e.g. test proficiency and strength).

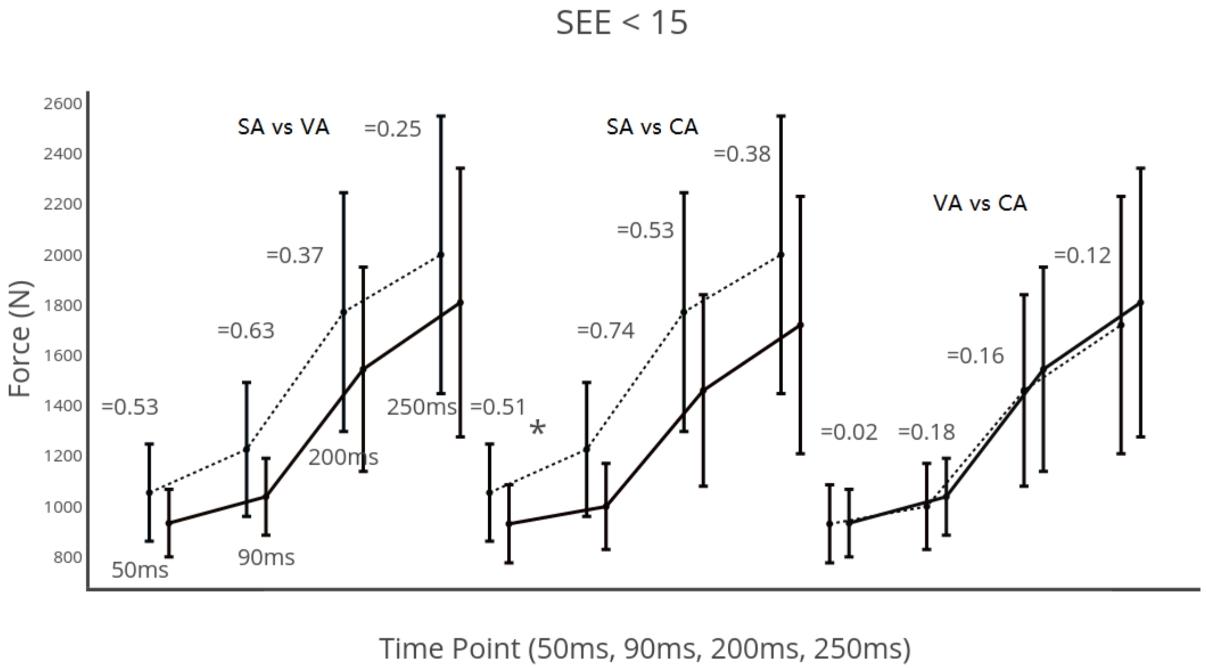

Figure 4.4 Force comparison under the shape of curves of ‘SEE<15’ between the threshold-based analysis (SA) and the other methods. (VA, visual analysis; CA, differential calculus-based analysis). In the first two groups of strips comparison, the dotted line was the DA. The dotted line in the third group of comparison was the MD. Mark ‘*’ indicated the interaction of different methods over two successive time points ($p<0.05$). The number over the strip of each column showed the cohen’s d between two methods.

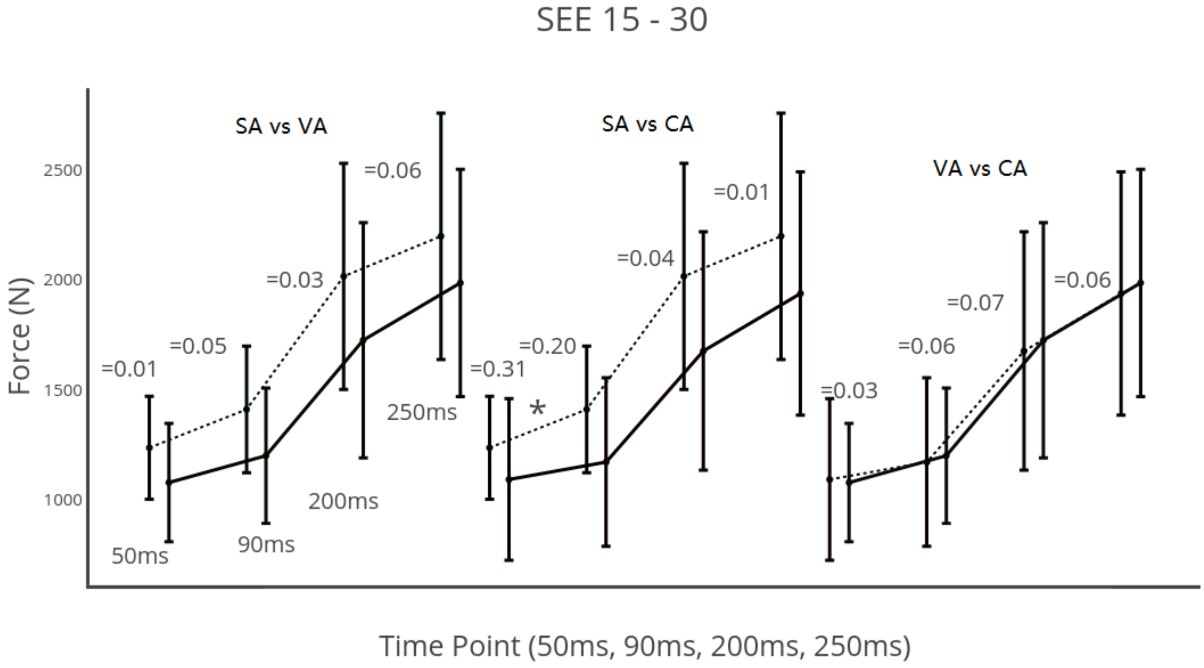

Figure 4.5 Force comparison under the shape of curves of 'SEE 15-30' between the threshold-based analysis (SA) and the other methods. Illustrations are the same as in the Figure 4.4.

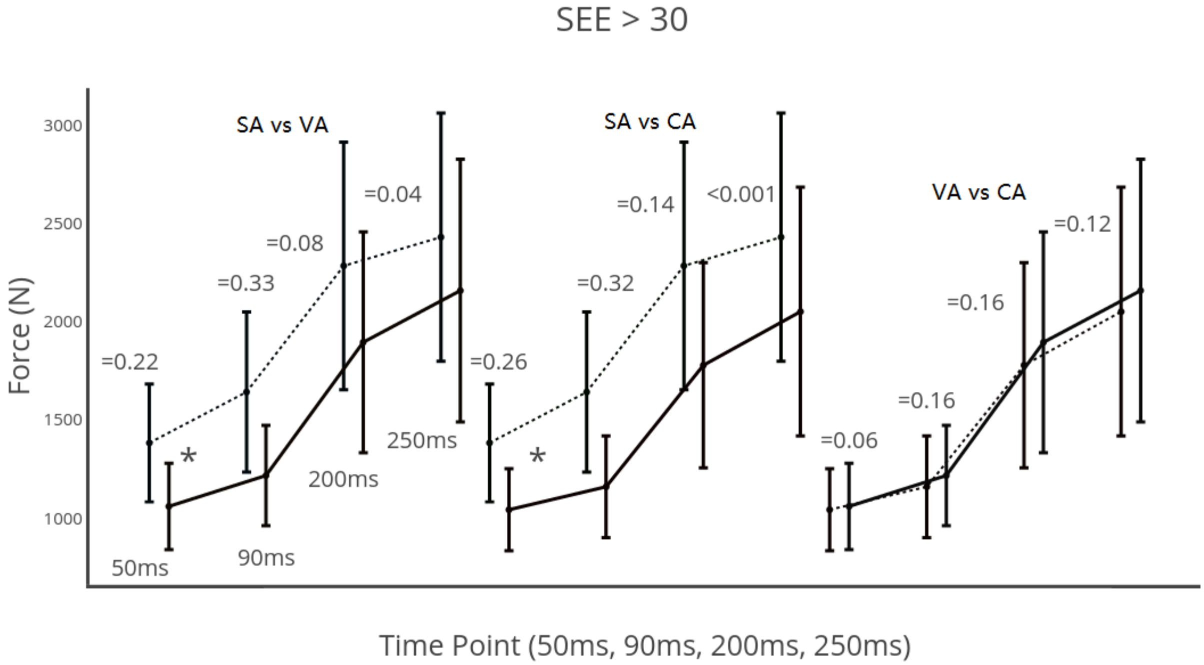

Figure 4.6 Force comparison under the shape of curves of 'SEE>30' between the threshold-based analysis (SA) and the other methods. Illustrations are the same as in the Figure 4.4.

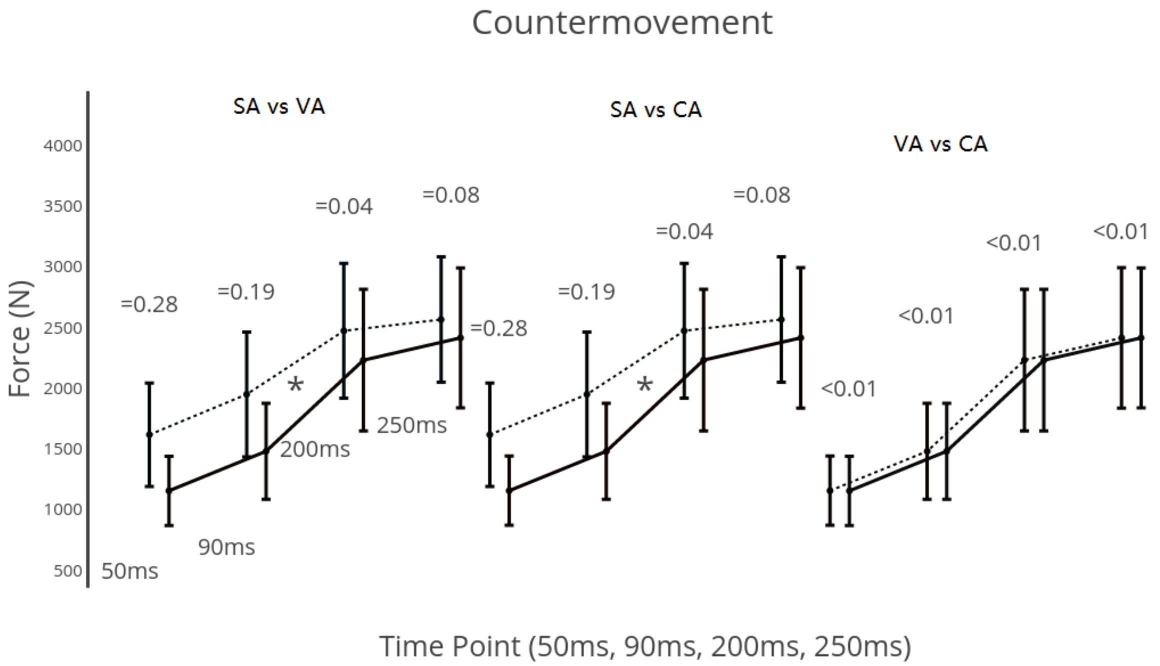

Figure 4.7 Force comparison under the shape of curves of ‘Countermovement’ between the threshold-based analysis (SA) and the other methods. Illustrations are the same as in the Figure 4.4.

Rate of Force Development

After five outliers were removed, the three-way mixed ANOVA with Greenhouse-Geisser adjustment indicated a statistical three-way interaction effect ($F_{(4.416, 104.518)} = 10.947$, $p < 0.001$). Thus, post hoc interaction contrasts with Scheffe adjustment (adjusted critical F = 10.859) were conducted at each level of baseline condition. The contrasts then showed the lack of statistical significance between VA and CA between any two adjacent time periods (Figures 4.8-11). However, statistical interactions were observed between VA or CA and SA. Without a countermovement in the baseline, statistical interactions were found only between 200ms and 250ms time periods at the SEE15-30 and SEE >30 levels while they were found between 50 and

90 and between 90 and 200 time periods with a countermovement. The interaction contrasts were followed up with simple comparisons between two methods at each time period under each baseline condition. In SEE <15, SA statistically differed from VA during 90 and from CA during 90, 200, and 250ms ($F_{(1, 70)}$ = 12.661-17.353). In SEE 15-30, SA differed from VA and CA during 50, 90, and 200ms ($F_{(1, 70)}$ = 12.053-20.552). In SEE >30, all methods differed from each other except for the comparison of VA to CA during 50ms ($F_{(1, 70)}$ = 13.177-59.606). In CM, SA differed from VA and CA during 50 and 90ms ($F_{(1, 70)}$ = 41.772-138.700).

Cohen's d was calculated in association with the simple comparisons between two methods at each time point in each baseline condition (Figures 4.8-11). Cohen's d values ranged from less than 0.01 to 0.72 when comparing VA and CA while they ranged from less than 0.01 to 1.58 when comparing VA or CA to SA. It appeared that greater Cohen's d values were observed more frequently with a countermovement and as SEE increased.

In order to examine the effect of baseline condition, interaction contrasts were performed between two baseline conditions between two methods during each time period. The results revealed statistical contrasts between CA and SA during 50ms when CM was compared to each of the other baseline conditions ($F_{(1, 70)}$ = 20.041-23.586).

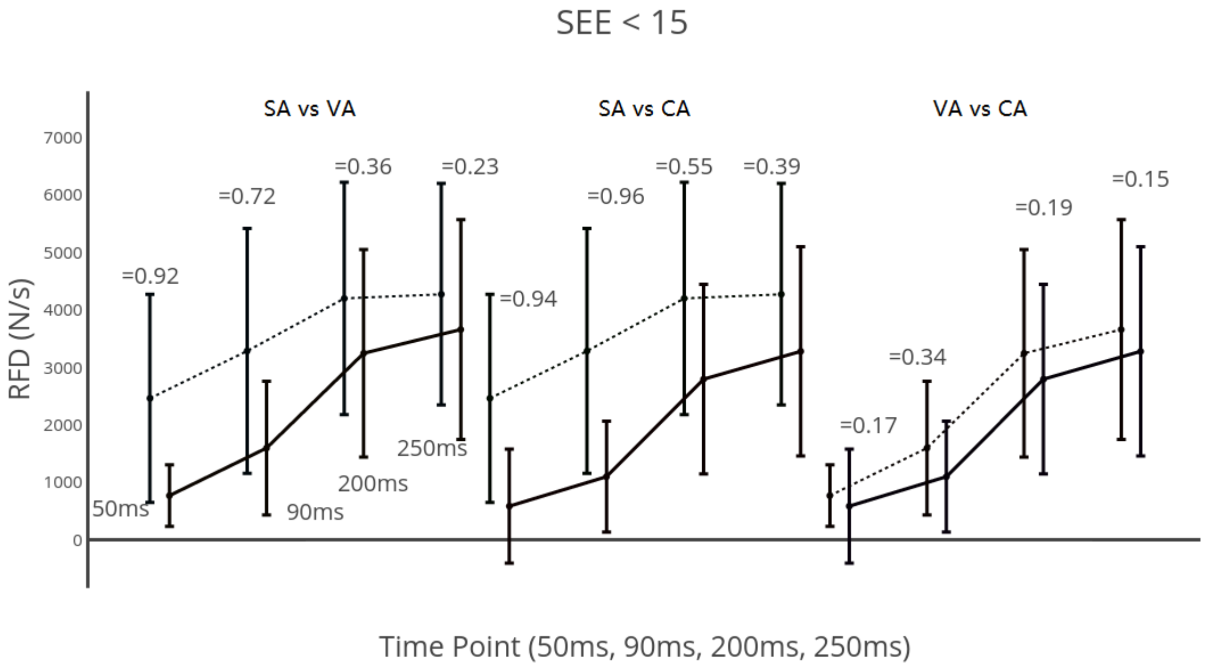

Figure 4.8 RFD comparison under the shape of curves of 'SEE<15' between the threshold-based analysis (SA) and the other methods. (VA, visual analysis; CA, differential calculus-based analysis) Mark '*' indicated the interaction of different methods over two successive time points ($p<0.05$). The number over the strip of each column showed the cohen's d between two methods.

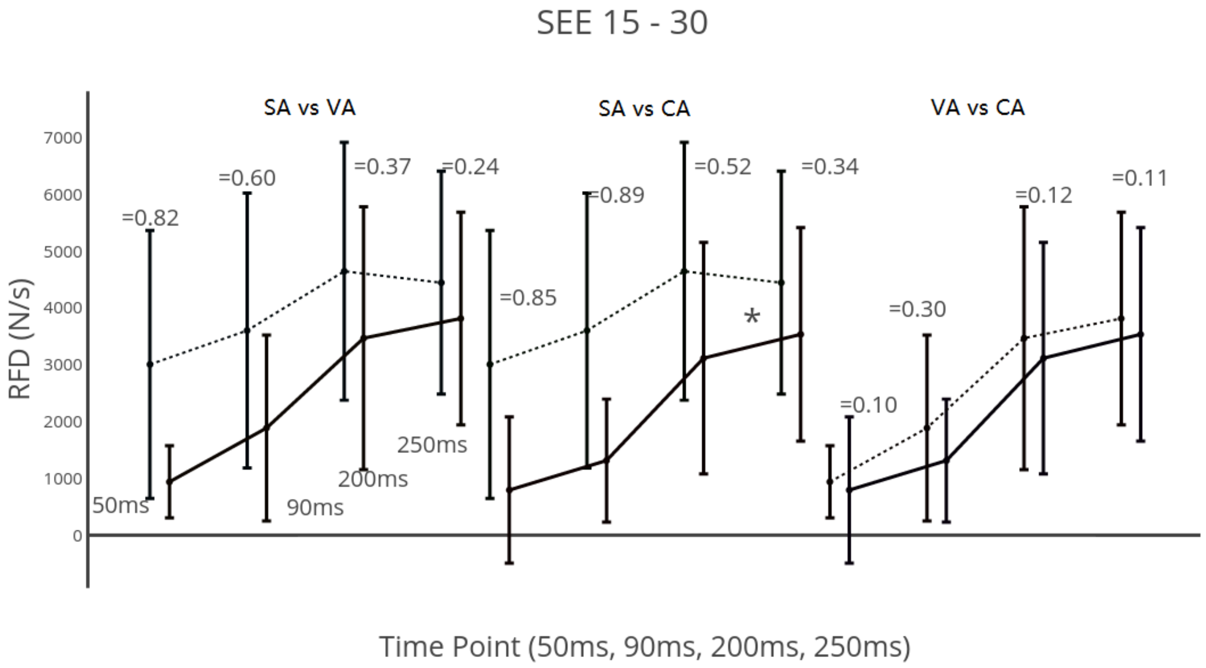

Figure 4.9 RFD comparison under the shape of curves of ‘SEE 15-30’ between the threshold-based analysis (SA) and the other methods. Illustrations are the same as in the figure 4.8.

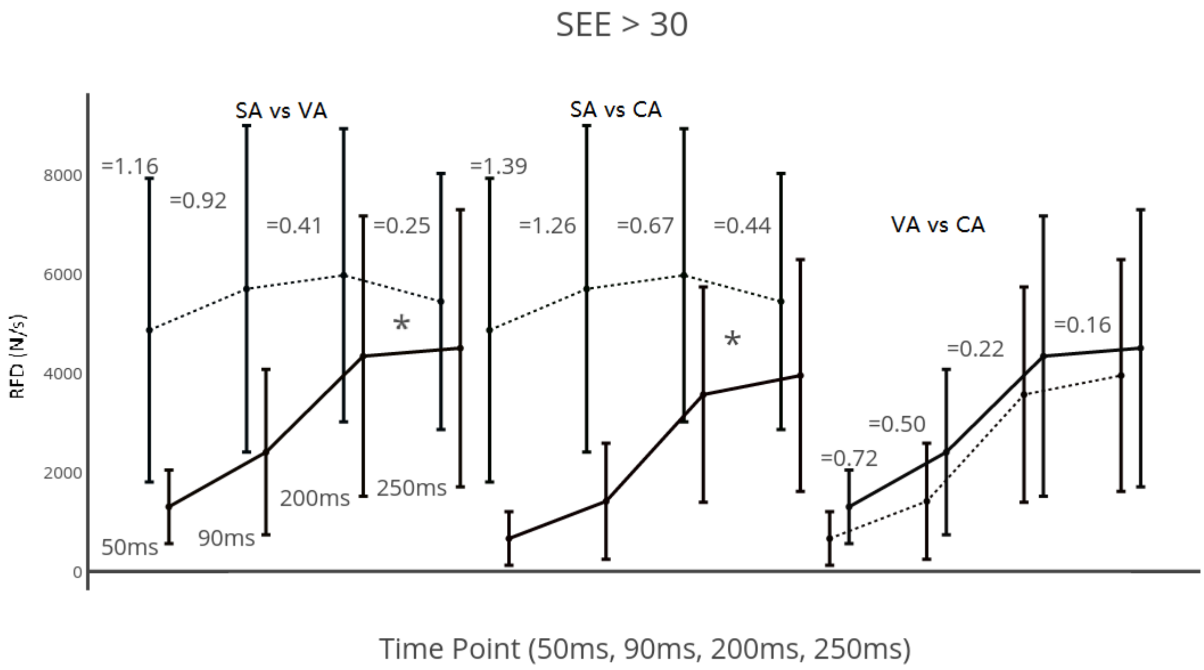

Figure 4.10 RFD comparison under the shape of curves of ‘SEE>30’ between the threshold-based analysis (SA) and the other methods.. Illustrations are the same as in the figure 4.8.

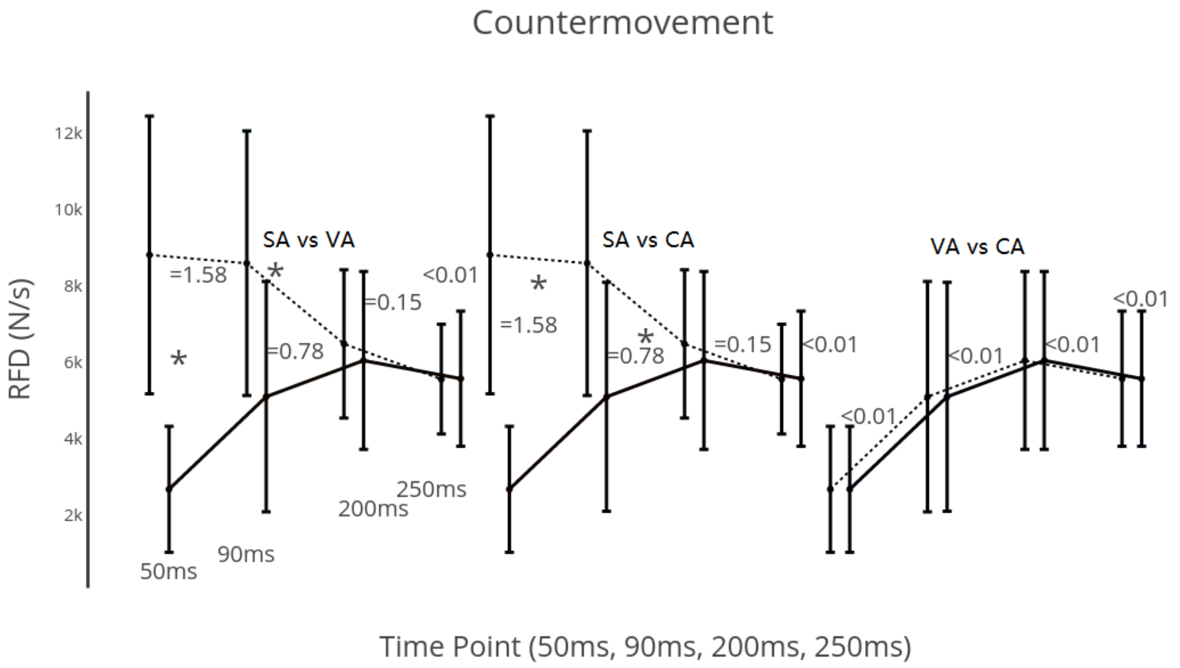

Figure 4.11 RFD comparison under the shape of curves of ‘Countermovement’ between the threshold-based analysis (SA) and the other methods. Illustrations are the same as in the figure 4.8.

Outlier Analysis

While outliers were removed from the data for the ANOVAs, they are provided here because they might offer unique insight for possible situations in which any of the three examined methods can produce erroneous values. It is important to note that outliers were determined based on the distribution in each cell of the conducted ANOVAs. A score may be determined as an outlier because of some error in a method affecting the score or because the athlete to whom the score belonged to had extremely high or low performance. While it is difficult to determine whether an outlier was due to error in a method, the individual outlier scores were compared for possible trends.

Instantaneous Force

Of the six outliers removed from the ANOVA, none were identified in the countermovement condition (Table 4.2). In general, VA appeared similar to one of the other two methods under all of the other three conditions. In other words, the third method appeared to produce a rather distinct value. For example, the values of subject 81 by SA were greater than the other two by approximately 400 to 1000N in the SEE >30 condition. Moreover, a distinct value was always greater than the corresponding values by the other two methods. The observation of a distinct value appeared to be more frequent for SA than CA.

Table 4.2 Outliers for Instantaneous Force (N)

SEE <15												
Outlier subject	50ms			90ms			200ms			250ms		
	VA	CA	SA	VA	CA	SA	VA	CA	SA	VA	CA	SA
38	1712*	1729	1910*	2147*	2170*	2379*	3198*	3214	3346	3501	3508	3552
	(3.15)	(2.23)	(2.81)	(3.35)	(2.58)	(2.80)	(2.71)	(2.55)	(2.40)	(2.33)	(2.37)	(2.16)
70	1324	1948*	1525	1584	2257*	1832	2452	3015	2736	2871	3090	3004
	(1.45)	(2.92)	(1.44)	(1.51)	(2.79)	(1.36)	(1.38)	(2.23)	(1.39)	(1.39)	(1.76)	(1.33)
SEE 15-30												
Outlier subject	50ms			90ms			200ms			250ms		
	VA	CA	SA	VA	CA	SA	VA	CA	SA	VA	CA	SA
112	1541	2462*	1672	2039	2948*	2194	3178	3027	3190	3077	3262	3039
	(1.29)	(2.62)	(1.05)	(1.83)	(2.83)	(1.40)	(1.73)	(1.58)	(1.42)	(1.30)	(1.51)	(1.02)
116	1782	1788	2341*	2211	2227	3007*	3742	3753	4096*	4101*	4103*	4064
	(2.05)	(1.22)	(3.00)	(2.25)	(1.58)	(3.11)	(2.49)	(2.56)	(2.69)	(2.74)	(2.61)	(2.50)
SEE >30												
Outlier subject	50ms			90ms			200ms			250ms		
	VA	CA	SA	VA	CA	SA	VA	CA	SA	VA	CA	SA
81	2264*	2257*	2657	2281	2279	3021	2342	2339	4142	2383	2379	4410
	(2.78)	(2.89)	(2.45)	(2.33)	(2.55)	(2.16)	(0.50)	(0.75)	(1.89)	(0.13)	(0.29)	(1.85)
149	2014	1937	2542	2315	2073	3035	3674	3313	4555	4422*	3994	5128*
	(2.15)	(2.06)	(2.21)	(2.41)	(2.04)	(2.18)	(2.50)	(2.34)	(2.36)	(2.64)	(2.47)	(2.61)
CM												
Outlier subject	50ms			90ms			200ms			250ms		
	VA	CA	SA	VA	CA	SA	VA	CA	SA	VA	CA	SA
No outlier	-	-	-	-	-	-	-	-	-	-	-	-

Asterisks indicate that the values were identified as outliers. The values without asterisks are provided for comparison. The values in parentheses are the corresponding z scores used to identify outliers.

Rate of Force Development

Similarly to the instantaneous force, there were no outliers in the countermovement condition out of the five outliers identified (Table 4.3). The same trend of one method producing a distinct value was also made. For example, the values of subject 116 by SA were greater than the other two by approximately 600 to 9000 N·/s in the SEE 15-30 condition. However, all three methods appeared to produce distinct values and some distinct values were smaller than the corresponding values by the other two unlike for the instantaneous force outliers.

Table 4.3 Outliers for Rate of Force Development (N/s)

SEE<15												
Outlier subject	50ms			90ms			200ms			250ms		
	VA	CA	SA	VA	CA	SA	VA	CA	SA	VA	CA	SA
38	2981 (2.53)	3311 (1.18)	6639 (1.87)	6487* (2.74)	6744 (2.41)	8898 (2.11)	8172 (2.13)	8253 (2.27)	8839 (1.87)	7751 (1.76)	7779 (1.99)	7893 (1.59)
70	2530 (1.96)	7588* (3.43)	5412 (1.27)	4291 (1.41)	7648* (2.84)	6420 (1.10)	6269 (1.24)	7229 (1.80)	7410 (1.24)	6692 (1.26)	6084 (1.18)	6999 (1.16)
SEE15-30												
Outlier subject	50ms			90ms			200ms			250ms		
	VA	CA	SA	VA	CA	SA	VA	CA	SA	VA	CA	SA
112	3827* (2.91)	12730* (3.83)	6264 (0.90)	7660 (2.41)	12472* (3.62)	9282 (1.44)	9144 (1.72)	6007 (0.92)	9158 (1.40)	6910 (1.15)	5746 (0.78)	6721 (0.89)
116	2287 (1.23)	2387 (0.31)	11290* (2.60)	6038 (1.67)	6205 (1.43)	13668* (2.72)	10372 (2.14)	10420* (2.63)	11597 (2.27)	9733 (2.38)	9739 (2.52)	9149 (2.00)
SEE>30												
Outlier subject	50ms			90ms			200ms			250ms		
	VA	CA	SA	VA	CA	SA	VA	CA	SA	VA	CA	SA
151	3136 (2.10)	6290* (3.92)	11059 (1.79)	4577 (1.22)	8783* (3.49)	10455 (1.34)	8258 (1.29)	10415 (2.49)	10840 (1.50)	9100 (1.50)	9924 (2.15)	9898 (1.56)
CM												
Outlier subject	50ms			90ms			200ms			250ms		
	VA	CA	SA	VA	CA	SA	VA	CA	SA	VA	CA	SA
No outlier	-	-	-	-	-	-	-	-	-	-	-	-

Asterisks indicate that the values were identified as outliers. The values without asterisks are provided for comparison. The values in parentheses are the corresponding z scores used to identify outliers.

DISCUSSION

The present study was to compare the visual examination analysis method (VA), a threshold-based analysis method (SA) such as that reported by Dos'Santos (3), and a differential calculus-based analysis method (CA) to analyze force-time curves of the IMTP test. It was expected differences between the methods if used in practical settings (1, 5, 6, 10). It was already known that the threshold-based method suggested by Dos Santos could have the smallest difference of onset time estimation. The study revealed its difference to the golden method of visual analysis to understand the practical meaning of threshold-based method. The visual analysis (VA) appears to be a more common method while the standard-deviation threshold-based method (SA) has been proposed recently (3). Besides the two, we examined a calculus-based method (CA). After examining the three methods, the primary findings of the study are 1) despite statistically trivial differences in the onset time, kinetic variables derived from force-time curves show more than trivial differences, 2) differences between the methods in rate of force development (RFD) values appear to increase as baseline undulation increases or with a countermovement, and 3) SA generally appears to produce greater values than the other two methods.

Onset Time

Onset time of a pull was examined because the onset is used as a reference point for calculations of other time-dependent variables such as instantaneous forces and RFDs at and during various time points and windows. The results of the onset time analysis suggest that the three methods all seem to produce comparable onset times based on the Cohen's d values (Figure 3.1). However, the presence of the method main effect and the group by method interaction effect, although post hoc interaction contrasts failed to show statistical significance, suggests that there was at least a trend of a method to consistently produce a different onset time compared to another method. In fact, the post pairwise comparisons for the main effect of method showed that all methods statistically differed from each other. Thus, it is important to note that, when examining a variable that occurs in a very short time period (e.g. 50 ms) after the onset of a pull, even a difference of Cohen's d less than 0.001 could lead to a practically important difference. In fact, as Cohen's d is an effect magnitude normalized to a pooled standard deviation, practically meaningful differences may be masked when means and standard deviations are larger than a difference of practical interest (e.g. 50 ms). Practitioners are encouraged to evaluate differences in actual onset time when selecting a method of analysis if variables of interest are time-dependent.

Instantaneous Force

The standard-deviation threshold-based method appears to produce greater instantaneous forces than the other two methods. In particular, statistically, SA appeared to diverge from the other two methods during an earlier period (e.g. 50-90ms) (Figures 3.2.1-3.2.4). Dotan et al. reported similar findings in that a threshold-based method tended to overestimate torque values (4). The simple comparisons indicated that SA method differed mostly from the other methods once SEE exceeded 15 N. This agrees with the notion that a method relying on a force threshold may be best used when the baseline is controlled (i.e. as level and straight as possible). However, it is also important to note that Cohen's d rarely exceeded a small effect between SA and the other methods.

Effects of baseline condition were considered with regard to the relative trend of difference between two methods at each time point. The results appear to suggest that the difference between CA and SA at 50ms increases with a countermovement. However, it is difficult to argue that an increase in baseline undulation represented with SEE lead to a greater difference between two methods given that Cohen’s d appeared to be trivial to small for most of the conditions and the results of the simple comparisons and interaction contrasts. This observation is somewhat surprising to the authors as it appeared logical to speculate that an increase in undulation would lead to a greater probability of false signaling of an onset of a pull and thus result in greater error. Despite the lack of a clear relationship between baseline condition and differences between two methods, SA does appear to perform most comparably to the other two methods when the baseline has no countermovement and is level and straight while the other methods may appear to perform more consistently under all examined baseline conditions.

Rate of Force Development

Similar to instantaneous force, SA appears to produce greater RFD values compared to VA or CA while VA and CA appear to maintain a trivial to small difference. However, contrary to instantaneous force, differences between SA and each of the other two methods appear to show a consistent pattern until 250ms, during which the differences appear to become smaller (i.e. SA begins to approach VA and CA). This observed pattern was exaggerated with a countermovement as indicated by trivial effect size during 200ms or 250ms and statistical interaction contrasts (Figure 3.3.4). In other words, RFD values by SA appears to differ more as a RFD time period becomes shorter.

Furthermore, the results of the simple comparisons suggest that as the baseline undulation increases, it becomes more likely that a method produces different RFD values from another method. In fact, with SEE >30N, all methods are likely to produce different RFD values than each other. However, the presence of a countermovement appears to help reduce differences among the methods in some cases. Specifically, there is unlikely to be a difference between VA and CA in all time periods and between SA and the other two methods during 200 and 250 ms.

Cohen’s d results suggest that the magnitude of difference remains mostly trivial to small between VA and CA while the magnitude of difference between SA and the other methods tends to be higher with more undulation in the baseline. Moreover, Cohen’s d results suggests that the presence of a countermovement seems to increase the difference between SA and the other methods during 50 and 90ms. In fact, the difference between CA and SA is likely to become greater with a countermovement as indicated by the interaction contrasts of method by baseline condition. In short, the baseline condition appears to influence differences between any two methods for RFD. The presence of countermovement appears to cause all methods to produce almost identical RFD values during longer time periods (e.g. 200 and 250ms) while the difference between SA and the other two methods appears to increase with a countermovement during shorter time periods.

Outliers

It is difficult to make inferences beyond our data by simple comparisons of individual outlier values. However, it appears that our observation of SA producing a distinct value in the outlier analysis is in agreement with the general trend observed in the ANOVA results for instantaneous force. This suggests the possibility that it was the exceptionally high or lower performance by the athletes that caused most of the outliers for the instantaneous force to be an outlier. On the other hand, for RFD, while the trend of a distinct value was observed, it is difficult to argue reasonably that there was a trend. The observed lack of a trend may appear surprising given the trend observed for instantaneous force. However, considering that the RFD calculation takes into account the force at the onset of a pull and the time elapsed since the onset, possible error in the identification of the onset of a pull can be manifested in a magnified manner in an RFD value.

The lack of an outlier under the countermovement condition may suggest that the presence of a countermovement in the baseline helps identify an onset more consistently within a method. This may be because the presence of a clear downward deflection can signal as the onset of a pull as a countermovement typically occurs immediately before the onset. In a typical isometric mid-thigh pull test protocol, a countermovement of up to 200N (1) is allowed although athletes are encouraged to not make a countermovement.

In conclusion, despite the trivial differences observed in the onset time, clear differences were observed in the instantaneous force and RFD values between the methods. Overall, VA and CA appear to produce values similar to each other for both instantaneous force and RFD under all conditions while SA appears to produce greater values than the other two. While the baseline condition does not appear to have a clear impact on instantaneous force values, it appears to do so on RFD values. In particular, an increase in the baseline undulation appears to increase the difference between any two methods. Furthermore, the presence of a countermovement appears to increase differences between SA and the other methods for RFD except for the 250ms time period. Based on the comparisons of individual outlier values, it should be noted that extreme values due to a defect in a method may be more likely for RFD possibly due to its calculation.

PRACTICAL APPLICATIONS

Practitioners are encouraged to seek a method that is most effective in their settings. If available modern technology can be exploited, a calculus-based method using a computer algorithm can offer advantage by fast data analysis that is more comparable to the visual examination method than a standard-deviation threshold-based method. A standard-deviation threshold-based method can be an option when the baseline of a force-time curve can be strictly controlled. If RFD is not a variable of interest, perhaps any of the methods may be an option. Last, given possible differences between methods, particularly in RFD values, practitioners should exercise caution for changing an analysis method in monitoring as the change in the analysis method can make it difficult to determine whether a change in an athlete's value is a real change.

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CHAPTER 5

SUMMARY AND FUTURE INVESTIGATIONS

Various sport performance tests are used in modern sport settings by sport coaches and sport scientists to monitor athletes and identify talents for particular sports. The isometric mid-thigh pull test (IMTP) is one such test, which has become more popular. What appears to be the most common method of analysis for the IMTP is by an experienced rater visually examining for an onset of a pull in a force-time curve of a trial (Haff et al., 2005; Haff et al., 1997; Stone et al., 2003). Upon detecting the onset, various time-dependent variables can be calculated including single-point forces and rates of force development. With the advancement of modern technology, it may be possible to create a computer-based analysis method that produces comparable values to those by the visual examination method in hopes to reduce the need of an experienced rater and reduce data analysis time. If possible, a resulting benefit of faster data return to coaches can be conceived and, ultimately generated data can have more time-sensitive values for athletes, whose conditions change over time.

Review of literature related to computer algorithm based methods to detect an onset of muscle contraction hinted on possible use of numerical analyses (Begg & Rahman, 2000; De Ruiter et al., 2007; Ghez, Hening, & Favilla, 1989; Heasman et al., 2000; Stelmach, Teasdale, Phillips, & Worringham, 1989). In this research project, we thus attempted to compare the visual examination method and computer algorithm based methods relying on numerical analyses. Furthermore, recently, a standard deviation threshold based method has been proposed specifically to detect an onset of a pull in the IMTP (Dos'Santos et al., 2017). Thus, we have also attempted to compare such a method to the other aforementioned methods. The purpose of this research project was to find a doable assistant method which is similar as visual analysis for entry-level practitioner in sport science to identify the onset time in the IMTP test.

Our first investigation compared the visual examination method to a number of computer algorithm methods that incorporated numerical analyses. The computer algorithm methods were based on first and second derivatives and curvature. The results of this investigation suggested possible use of first derivative for values most comparable to those of the visual examination method when a force-time curve contains a countermovement immediately prior to the rapid rise of force leading to peak force as supported by the lack of statistical significance and trivial effect sizes. They also suggested possible use of second derivative when a force-time curve does not have a countermovement with some concern for early rate of force development. Collectively, the major finding of the investigation is that computer algorithms based on first and second derivatives may be able to replace most of the visual examination work. A computer algorithm written to differentiate force-time curves based on the presence of a countermovement can optimize compatibility of the application of first and second derivative with the visual examination method for analysis of force-time curves generated during the IMTP. At the same time, there are a few caveats that practitioners should be aware of when applying first and second derivatives as done in this research project. The first caveat is that differences in onset time between the application of second derivative and the visual examination method, no matter how small they may be, can be magnified in rate of force development. In particular, early rate of force development may be impacted more than its late counter-parts as indicated by four moderate effect sizes – two in SEE 15-30 and two in SEE >30. The second caveat is that despite the major finding, examination of outliers hint that the application of second derivative can produce the magnitude of error larger than the application of first derivative when either of or both methods produce values that appear rather different than similar to those of the visual examination method.

Our second investigation compared a computer algorithm based method incorporating the first and second derivatives as suggested after the first investigation and another computer algorithm based method incorporating a standard deviation threshold to the visual examination method. The results of the second investigation showed expected compatibility between the visual examination method and the first and second derivative combined method. This was particularly true for single-point force values as supported by trivial effect sizes and the lack of statistical significance when compared to the visual examination method. For rate of force development, the first and second derivative combined method was generally less compatible as supported by four small effect sizes and one moderate effect size with the lack of statistical significance. On the other hand, the standard deviation threshold-based method had statistical differences with effect size mostly in the small to moderate range for single point forces and in the moderate to large range for rate of force development when compared to the visual examination method. Effect size appeared larger for the standard deviation threshold-based method than for the first and second derivative combined method even when the baseline of a force-time curve prior to the onset of a pull had SEE < 15 – one of all examined conditions in which the standard deviation threshold based method was expected to perform the best. The major finding of the investigation is that the second investigation's results confirmed the potential of the first and second derivative combined method as a replacement for most of the visual examination work. However, as expected, the method does appear to produce values with error from time to time. In particular, the magnitude of error appears to be larger for rate of force development. The standard deviation threshold-based method, while reported to be reliable, may need a less undulating baseline prior to the onset of a pull than the level of undulation considered in this study to produce values more comparable to those by the visual examination method.

In conclusion, the application of first and second derivatives appears to hold potential for producing values comparable to those by an experienced rater in the IMTP under a range of baseline conditions. While the first and second derivative combined method does appear to produce erroneous values, perhaps the frequency of erroneous values is small enough that visual examination analysis by an experienced rater can supplement where the method fails in practical settings. It is ideal to obtain a force-time curve with no countermovement and a level and straight baseline. However, it may be argued that such effort can be difficult when dealing with a large number of athletes with limited staff. While clear criteria for invalid trials should be followed, a commonly used protocol of the IMTP appears to allow for room for a small countermovement (less than approximately 200N from an estimated baseline force) and an unspecified level of baseline undulation (Bailey et al., 2015; Travis et al., 2018). As such, the analysis method should perhaps adapt in order to maintain the practicality of the test as well as to speed up data return to coaches and athletes. For practical recommendations, practitioners are recommended to evaluate resources available to themselves and the amount of data to be dealt with when choosing an analysis method for the IMTP. When appropriate resources are available, the first and second derivative combined method as examined in this research project may prove to be useful. Practitioners should also exercise caution when changing an analysis method as a change in an athlete’s value from the IMTP test could be due to the difference in the methods rather than a change in the athlete.

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APPENDICES

Appendix A

Table 1.1 Movement Onset Identification Methods

Authors	Publication year	Variables	onset detection method	Minimal countermovement allowed?
Haff, G. G., Stone, M., O'Bryant, H. S., Harman, E., Dinan, C., Johnson, R., & Han, K.-H.	1997	Peak force, maximum rate of force development	Visual	N/A
Haff, G. G., Carlock, J. M., Hartman, M. J., & Kilgore, J. L.	2005	Peak force, maximum rate of force development	N/A	N/A
McGuigan, M. R., Winchester, J. B., & Erickson, T.	2006	Peak force, maximum rate of force development	N/A	N/A

Haff, G. G., Jackson, J. R., Kawamori, N., Carlock, J. M., Hartman, M. J., Kilgore, J. L., Stone, M. H.	2008	Peak force, maximum rate of force development	N/A	N/A
McGuigan, M. R., & Winchester, J. B.	2008	Peak force, maximum rate of force development	N/A	N/A
Nuzzo, J. L., Mcbride, J. M., Cormie, P., & Mccaulley, G. O.	2008	Peak force, maximum rate of force development	N/A	N/A
Haff, G., Ruben, R., Molinari, M., Painter, K., Ramsey, M., Stone, M., & Stone, M.	2010	Peak force, maximum rate of force development	N/A	N/A
Lamont, H. S., Cramer, J. T., Bemben, D. A., Shehab, R. L., Anderson, M. A., & Bemben, M. G.	2010	Peak force	N/A	N/A

Mcguigan, M. R., Newton, M. J., Winchester, J. B., & Nelson, A. G.	2010	Peak force, maximum rate of force development	N/A	N/A
Khamoui, A. V., Brown, L. E., Nguyen, D., Uribe, B. P., Coburn, J. W., Noffal, G. J., & Tran, T.	2011	Peak force, maximum rate of force development	N/A	N/A
Alkatan, M. F., Dowling, E. A., Branch, J. D., Grieco, C., Kollock, R. O., & Williams, M. H.	2011	Peak force, maximum rate of force development	N/A	N/A
Sheppard, J., Chapman, D., & Taylor, K.-L.	2011	Peak force	N/A	N/A

Beckham, G. K., Lamont, H. S., Sato, K., Ramsey, M. W., & Stone, M. H.	2012	Peak force	Visual	Yes
Crewther, B., Kilduff, L., Cook, C. J., Cunningham, D., Bunce, P., Bracken, R., & Gaviglio, C.	2012	Peak force, maximum rate of force development, instantaneous force	N/A	N/A
Crewther, B., Kilduff, L., Cook, C., Cunningham, D., Bunce, P., Bracken, R., & Gaviglio, C.	2012	Peak force	N/A	N/A
Beckham, G., Mizuguchi, S., Carter, C., Sato, K., Ramsey, M., Lamont, H., Stone, M.	2013	Peak force, maximum rate of force development, instantaneous force	Visual	N/A

Bailey, C., Sato, K., Alexander, R., Chiang, C.-Y., & Stone, M. H.	2013	Peak force	Visual	N/A
Conlon, J., Haff, G. G., Nimphius, S., Tran, T., & Newton, R. U.	2013	Peak force, maximum rate of force development	N/A	N/A
Hornsby, W., Haff, G., Sands, W., Ramsey, M., Beckham, G., Stone, M., & Stone, M.	2013	Peak force, maximum rate of force development, time specific impulse, instantaneous force	Visual	N/A
Tran, T. T., Lundgren, L., Nimphius, S., Haff, G. G., Newton, R. U., & Sheppard, J. M.	2013	Peak force	N/A	N/A

Bailey, C. A., Sato, K., Burnett, A., & Stone, M. H.	2015	Peak force, maximum rate of force development, peak impulse, instantaneous force	Visual	Yes (<200N)
Avila, B. J., Brown, L. E., Coburn, J. W., & Statler, T. A.	2015	Instantaneous rate of force development	N/A	N/A
Bellar, D., LeBlanc, N. R., & Campbell, B.	2015	Peak force	N/A	N/A
Cazás-Moreno, V. L., Gdovin, J. R., Williams, C. C., Allen, C. R., Fu, Y.-C., Brown, L. E., & Garner III, J. C.	2015	Peak force, maximum rate of force development	N/A	N/A
Davies, M.	2015	Peak force	N/A	N/A
Haff, G. G., Ruben, R. P., Lider, J., Twine, C., & Cormie, P.	2015	Peak force, maximum rate of force development, instantaneous force	N/A	N/A

Herrington, L., Comfort, P., & Ghulam, H.	2015	Peak force, maximum rate of force development	N/A	N/A
Mangine, G. T., Hoffman, J. R., Gonzalez, A. M., Townsend, J. R., Wells, A. J., Jajtner, A. R., Wang, R.	2015	Peak force, maximum rate of force development, instantaneous force	N/A	N/A
McMahon, J. J., Turner, A., & Comfort, P.	2015	Peak force	Visual	N/A
Secomb, J. L., Farley, O. R., Lundgren, L., Tran, T. T., King, A., Nimphius, S., & Sheppard, J. M.	2015	Peak force	N/A	N/A
Sjökvist, J., Sandbakk, Ø., Willis, S. J., Andersson, E., & Holmberg, H.-C.	2015	Peak force	N/A	N/A

Spiteri, T., Newton, R. U., Binetti, M., Hart, N. H., Sheppard, J. M., & Nimphius, S.	2015	Peak force, instantaneous force	N/A	N/A
Tran, T. T., Lundgren, L., Secomb, J., Farley, O. R., Haff, G. G., Seitz, L. B., . . . Sheppard, J. M.	2015	Peak force	N/A	N/A
Welch, N., Moran, K., Antony, J., Richter, C., Marshall, B., Coyle, J., Franklyn-Miller, A.	2015	Peak force	N/A	N/A
Secomb, J. L., Lundgren, L. E., Farley, O. R., Tran, T. T., Nimphius, S., & Sheppard, J. M.	2015	Peak force	N/A	N/A

Thomas, C., Comfort, P., Chiang, C.-Y., & Jones, P. A.	2015	Peak force, maximum rate of force development, time specific impulse	Visual	N/A
Secomb, J. L., Nimphius, S., Farley, O. R., Lundgren, L. E., Tran, T. T., & Sheppard, J. M.	2015	Peak force	N/A	N/A
Crewther, B., Carruthers, J., Kilduff, L., Sanctuary, C., & Cook, C.	2016	Peak force	N/A	N/A
Dos' Santos, T., Jones, P. A., Kelly, J., McMahon, J. J., Comfort, P., & Thomas, C.	2016	Peak force, instantaneous force	5SD Baseline	N/A
Garrett, J. M., McKeown, I., & Rogers, D. K.	2016	Peak force	N/A	N/A

Gillen, Z. M., Wyatt, F. B., Winchester, J. B., Smith, D. A., & Ghetia, V.	2016	Peak force, maximum rate of force development, time specific impulse	N/A	N/A
Halperin, I., Williams, K. J., Martin, D. T., & Chapman, D. W.	2016	Peak force	N/A	N/A
Wang, R., Hoffman, J. R., Tanigawa, S., Miramonti, A. A., La Monica, M. B., Beyer, K. S., Stout, J. R.	2016	Peak force, maximum rate of force development	N/A	N/A
Thomas, C., Comfort, P., Jones, P. A., & Dos'Santos, T.	2016	Peak force, peak force left, peak force right	N/A	N/A
South, M., Layne, A., Stuart, C. A., Triplett, N. T., Ramsey, M., Howell, M., Kavanaugh, A.	2016	Peak force, maximum rate of force development	Visual	N/A

Bartolomei, S., Sadres, E., Church, D. D., Arroyo, E., Gordon III, J. A., Varanoske, A. N., Stout, J. R.	2017	Peak force, maximum rate of force development	N/A	N/A
Boccia, G., Fornasiero, A., Savoldelli, A., Bortolan, L., Rainoldi, A., Schena, F., & Pellegrini, B.	2017	Peak force	N/A	N/A
Beattie, K., Carson, B. P., Lyons, M., & Kenny, I. C.	2017	Peak force	N/A	N/A
Brady, C. J., Harrison, A. J., Flanagan, E. P., Haff, G. G., & Comyns, T. M.	2017	Peak force, instantaneous force, maximum rate of force development	5SD baseline threshold	N/A

Carroll, K. M., Wagle, J. P., Sato, K., DeWeese, B. H., Mizuguchi, S., & Stone, M. H.	2017	Peak force, maximum rate of force development	Visual	N/A
Casadio, J. R., Storey, A. G., Merien, F., Kilding, A. E., Cotter, J. D., & Laursen, P. B.	2017	Peak force	N/A	N/A
Clarke, N. D., Hammond, S., Kornilios, E., & Mundy, P. D.	2017	Peak force	N/A	N/A
Dobbin, N., Hunwicks, R., Jones, B., Till, K., Highton, J., & Twist, C.	2017	Peak force	N/A	N/A
Edwards, R. B., Tofari, P. J., Cormack, S. J., & Whyte, D. G.	2017	Peak force	N/A	N/A

Emmonds, S., Morris, R., Murray, E., Robinson, C., Turner, L., & Jones, B.	2017	Peak force, time specific impulse	N/A	N/A
Hornsby, W. G., Gentles, J. A., MacDonald, C. J., Mizuguchi, S., Ramsey, M. W., & Stone, M. H.	2017	Peak force, maximum rate of force development	Visual	N/A
Ireton, M., Till, K., Weaving, D., & Jones, B.	2017	Peak force	N/A	N/A
James, L. P., Roberts, L. A., Haff, G. G., Kelly, V. G., & Beckman, E. M.	2017	instantaneous rate of force development, instantaneous force	20N	N/A
Kuki, S., Sato, K., Stone, M. H., Okano, K., Yoshida, T., & Tanigawa, S.	2017	Peak force, instantaneous force	Visual	N/A

Marcus, L., Soileau, J., Judge, L. W., & Bellar, D.	2017	Peak force	N/A	N/A
Maulit, M. R., Archer, D. C., Leyva, W. D., Munger, C. N., Wong, M. A., Brown, L. E., Galpin, A. J.	2017	Peak force, maximum rate of force development	N/A	N/A
McMahon, J. J., Jones, P. A., Suchomel, T. J., Lake, J., & Comfort, P.	2017	Peak force	N/A	N/A
McMaster, D. T., Beaven, C. M., Mayo, B., Gill, N., & Hébert-Losier, K.	2017	Peak force	N/A	N/A
Oranchuk, D. J., Robinson, T. L., Switaj, Z. J., & Drinkwater, E. J.	2017	Peak force	2.5% BW	N/A

Scott, B. R., Slattery, K. M., Sculley, D. V., & Dascombe, B. J.	2017	Peak force	N/A	N/A
Townsend, J. R., Bender, D., Vantrease, W., Hudy, J., Huet, K., Williamson, C., Mangine, G. T.	2017	Peak force, instantaneous force, peak rate of force development	N/A	N/A
Tran, T. T., Lundgren, L., Secomb, J., Farley, O. R., Haff, G. G., Nimphius, S., Sheppard, J. M.	2017	Peak force	N/A	N/A
Urquhart, M., Bishop, C., & Turner, A. N.	2017	instantaneous force	N/A	N/A
Thomas, C., Comfort, P., Dos'Santos, T., & Jones, P. A.	2017	Peak force	N/A	N/A

Dos' Santos, T., Thomas, C., Jones, P. A., McMahon, J. J., & Comfort, P.	2017	Peak force, instantaneous force	5% BW	Yes (<200N)
Thomas, C., Comfort, P., Jones, P. A., & Dos' Santos, T.	2017	Peak force, maximum rate of force development, time specific impulse	40N	N/A
Thomas, C., Comfort, P., Jones, P. A., & Dos' Santos, T.	2017	Peak force	N/A	N/A
Thomas, C., Dos'Santos, T., Comfort, P., & Jones, P. A.	2017	Peak force	N/A	N/A
Dos' Santos, T., Jones, P. A., Comfort, P., & Thomas, C.	2017	Peak force, net peak force, instantaneous force, maximum rate of force development, time specific net impulse	5SD baseline threshold	No

Allen, C. R., Fu, Y.-C., Cazas-Moreno, V., Valliant, M. W., Gdovin, J. R., Williams, C. C., & Garner, J. C.	2018	Peak force, maximum rate of force development	N/A	N/A
Beckham, G., Mizuguchi, S., Carter, C., Sato, K., Ramsey, M., Lamont, H., Stone, M.	2018	Peak force, instantaneous force	Visual	N/A
Bender, D., Townsend, J. R., Vantrease, W., Marshall, A. C., Henry, R. N., Heffington, S., & Johnson, K. D.	2018	Peak force	N/A	N/A
Brownlee, T. E., Murtagh, C. F., Naughton, R. J., Whitworth-Turner, C. M., O’Boyle, A., Morgans, R., Drust, B.	2018	Peak force	N/A	N/A

Taber, C., Carroll, K., DeWeese, B., Sato, K., Stuart, C., Howell, M., Stone, M.	2018	Peak force	N/A	N/A
Comfort, P., Thomas, C., Dos' Santos, T., Jones, P. A., Suchomel, T. J., & McMahon, J. J.	2018	instantaneous force	N/A	N/A
De Witt, J. K., English, K. L., Crowell, J. B., Kalogera, K. L., Guilliams, M. E., Nieschwitz, B. E., Ploutz-Snyder, L. L.	2018	Peak force, instantaneous force, maximum rate of force development	N/A	N/A
Hayes, M. J., Spits, D. R., Watts, D. G., & Kelly, V. G.	2018	Peak force, time specific impulse	N/A	N/A
Mijwel, S., Backman, M., Bolam, K. A., Olofsson, E.,	2018	Peak force	N/A	N/A

Norrbom, J., Bergh, J., Rundqvist, H.				
Orange, S. T., Marshall, P., Madden, L. A., & Vince, R. V.	2018	instantaneous force	N/A	N/A
Sawczuk, T., Jones, B., Scantlebury, S., Weakley, J., Read, D., Costello, N., Till, K.	2018	instantaneous force	N/A	N/A
Moeskops, S., Oliver, J. L., Read, P. J., Cronin, J. B., Myer, G. D., Haff, G. G., & Lloyd, R. S.	2018	Peak force, instantaneous force, maximum rate of force development	N/A	N/A
Travis, S. K., Goodin, J. R., Beckham, G. K., & Bazyler, C. D.	2018	Peak force, maximum rate of force development	Visual	Yes (<200N)

Vercoe, J., & R McGuigan, M.	2018	Peak force, maximum rate of force development	N/A	N/A
Wells, J. E., Mitchell, A. C., Charalambous, L. H., & Fletcher, I. M.	2018	Peak force, maximum rate of force development	N/A	N/A
Dos' Santos, T., Thomas, C., Jones, P. A., & Comfort, P.	2018	Peak force, time specific impulse	40N	N/A
Dos' Santos, T., Lake, J., Jones, P. A., & Comfort, P.	2018	Peak force, instantaneous force	5SD baseline threshold	Yes (<200N)

Appendix B

Table 1.2 Studies exemplifying various methods of onset detection reported in sport and exercise science.

Onset Detection Method	Studies	Study Description	Special Notes
Visual	Pulkovski, N., Schenk, P., Maffiuletti, N. A., & Mannion, A. F. (2008)	Validation of Doppler Imaging for muscle activity onset detection.	Visual detection
	Tillin, N. A., Jimenez-Reyes, P., Pain, M. T., & Folland, J. P. (2010).	Examined a difference in electromechanical delay and rate of force development	A systematic approach of visual detection, checked against first derivative.
Threshold-based	Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., & Dyhre-Poulsen, P. (2002)	Examination of effects of resistance training on contractile rate of force development and efferent motor outflow.	Threshold used: 7.5Nm for absolute rate of force develop or 2.5% MVC for normalized rate of force development

	De Ruiter, C. J., Leeuwen, D., Heijblom, A., Bobbert, M. F., & Haan, A. d. (2006)	Examination of relationships between rate of isometric torque development during the first 40ms and vertical jump	Threshold used: 3 x baseline SD above mean baseline torque & 10N above the lowest ground reaction force during baseline.
	Dos' Santos, T., Jones, P. A., Comfort, P., & Thomas, C. (2017)	Reliability of various thresholds for onset detection in the isometric mid-thigh pull test	Threshold used: 5 x baseline SD above mean baseline force, 2.5, 5, and 10% above mean baseline force, and 75N above mean baseline force. 5 x baseline SD above mean baseline force found to be most reliable.
	Dotan, R., Jenkins, G., O'Brien, T. D., Hansen, S., & Falk, B. (2016).	Comparison of threshold-based methods to visual detection in explosive isometric knee extension	Threshold used: 4 Nm & 5% MVC. Threshold methods tended to misreprent onset.

	Karst, G. M., & Willett, G. M. (1995)	Muscle activity of the quadriceps of asymptomatic subjects and subjects with patellofemoral pain syndrome.	Standard deviation based threshold supplemented by visual detection
Differential Calculus	Ghez, C., Hening, W., & Favilla, M. (1989)	Examination of human responses to a target and its trajectory	The point of the first change in first derivative of a force-time curve used as an onset.
Others	Bonato, P., D'Alessio, T., & Knaflitz, M. (1998)	Examination of a statistical method for on and off muscle activity in electromyography.	Probability of presence of muscle activity is estimated using various statistical techniques such as whitening filter and probability density function. Estimated error in on & off activity detection was less than 10ms.
	Ikemoto, Y., Demura, S., & Yamaji, S. (2004)	Relationships between inflection point on a force-time curve and explosive	Intersection of two regression lines as onset. The first regression line was fitted to the phase in which

		muscle contraction in hand grip exercise	force developed rapidly and the second line was fitted to the phase in which force plateaued near peak force.
	Li, X., & Aruin, A. S. (2006)	Application of Teager-Kaiser energy operator for onset detection in electromyopgraphic data.	Teager-Kaiser energy operator appeared to perform superiorly to a threshold-based method, a wavelet transformation method, and a statistical method (generalized likeliness ratio). The proposed method appears simple. However, the performance may depend on the signal to noise ratio of time-series data.
	Liebermann, D. G., & Goodman, D. (2007)	Examination of the effect of continuous vision and its occlusion in	A method based on changes in a correlation coefficient between the

		timing of pre-landing actions during free falls. Electromyography was used to monitor muscle activity during a fall under different conditions.	number of samples and electromyography amplitude was found to detect onset earlier than visual detection.
	Micera, S., Sabatini, A. M., & Dario, P. (1998)	Examination of a algorithm for onset detection in electromyography. The algorithm is based on the Generalized Likelihood Ratio test.	Use of the algorithm reported to provide more accurate onset detection than threshold-based methods.
	Soda, P., Mazzoleni, S., Cavallo, G., Guglielmelli, E., & Iannello, G. (2010)	Examination of a decision-making algorithm for selecting the most suitable onset detection method for kinetic data. Various onset detection methods were examined with visual detection as a criterion for various tasks.	Threshold used: 2%, 4%, 6%, 8%, and 10% of peak force or torque. Three methods based on second derivative. A method based on the kernel smoothing function. Performance of individual methods as well as decision-making algorithms was reported.

	Staude, G. H. (2001)	Application of statistical signal processing for onset detection in kinematic data.	The suggested approach, the AGLR method, produced the most comparable results to visual detection than a threshold-based and low-pass differentiator methods.
	Teasdale, N., Bard, C., Fleury, M., Young, D. E., & Proteau, L. (1993)	Examination of various onset detection methods for their detection accuracy. Algorithms based on a pre-defined tolerance range in percentage of the maximum amplitude in each trial were compared to visual detection as well as a absolute threshold-based method.	All methods showed problems in accurate onset detection.

VITA

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