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Erich J. Petushek

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**COMPARISON OF COUNTERMOVEMENT JUMP AND LANDING KNEE  
ANGLE: 2D VIDEO VS ELECTROGONIOMETRY**

By

Erich J. Petushek

THESIS

Submitted to

Northern Michigan University

In partial fulfillment of the requirements

For the degree of

MASTER OF SCIENCE

Graduate Studies Office

2011

## SIGNATURE APPROVAL FORM

This thesis by Erich J. Petushek is recommended for approval by the student's thesis committee in the Department of Health, Physical, Education and Recreation and by the Dean of Graduate Studies.

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Date of Birth: July, 3, 1987

## ABSTRACT

### COMPARISON OF COUNTERMOVEMENT JUMP AND LANDING KNEE ANGLE: 2D VIDEO VS ELECTROGONIOMETRY

By

**Erich J. Petushek**

Quantifying countermovement jump and landing knee angle is important for performance and injury risk assessment. The purpose of the study was to compare electrogoniometer and video derived countermovement jump and landing knee flexion angle. Twenty-two adults performed three countermovement jumps while knee angle was simultaneously assessed using an El-Gon and video. The average error of the El-Gon derived knee angle was  $7.03 \pm 2.69^\circ$ . Excellent reliability was demonstrated by the El-Gon ( $ICC_{avg} = 0.92$ ). Countermovement knee angle, maximum landing knee angle and angle at maximum vertical ground reaction force were 12.0, 10.9, and  $5.7^\circ$  higher, respectively, when assessed using El-Gon ( $p < 0.001$ ), compared to video. Errors between instruments are likely due to El-Gon cross-talk, misalignment and/or axis determination. The El-Gon is a cost effective and time efficient alternative to video analysis for the assessment of knee angle if the error is accounted for and the sensor is precisely attached.

**Keywords:** Accuracy, reliability, El-Gon, motion analysis, angular kinematics

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## PREFACE

This thesis follows the format prescribed by the International Sports Engineering Associations' Sports Engineering Journal as recommended by the Department of Health, Physical Education, and Recreation.

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## I. MANUSCRIPT SUBMISSION

### COMPARISON OF COUNTERMOVEMENT JUMP AND LANDING KNEE ANGLE: 2D VIDEO VS ELECTROGONIOMETRY

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## **1 Introduction**

The countermovement jump (CMJ) is performed in a variety of sports and is commonly used to assess the effectiveness of training protocols and lower body power [1].

Additionally, the impact from CMJ landing has been associated with both acute and chronic lower extremity injuries [2]. Therefore, the CMJ is a versatile exercise used to assess both performance and injury risk in many populations.

Knee joint angle during the descent phase of the CMJ is an important biomechanical variable that influences the outcome of the CMJ. Specifically, the maximum countermovement depth or knee angle has a significant effect on jump height, lower body peak torque and muscle activation [3, 4]. An increase in countermovement knee angle has also been shown to be a beneficial adaptation following plyometric training [5]. Additionally, knee angle during the CMJ was important for determining motor development progression in adolescents [6]. Therefore, quantifying knee angle during the descent or countermovement phase of the CMJ reveals important information regarding the effectiveness of the movement and may provide information useful for the prevention of injuries.

In addition to the descent phase, the countermovement jump landing knee angle influences the forces transmitted throughout the body's tissues. When excessive, these impact forces have been associated with various knee injuries, including tendinitis, anterior cruciate ligament (ACL) injury, and osteoarthritis [2, 7]. Knee flexion angle during jump landing significantly predicted patellar tendinitis in volleyball athletes [8] as well as aided in the prediction of ACL injury in high school female athletes [9]. Quantitative assessment of jump landing knee angle would therefore be important for

athletic screening and evaluation purposes. Current video methods to assess landing knee angle rely on labor intensive analysis procedures limiting the application to research settings. Thus, some questions exist about the best and most practical methods to assess jump landing dynamics.

Technological advances in the field of biomechanics have revealed data acquisition equipment that is more affordable, portable and user friendly. Motion analysis has been the “gold standard” in dynamic knee angle quantification; however this method relies on expensive cameras and time intensive analysis procedures. The flexible electrogoniometer (El-Gon) is simple to operate, affordable and allows for instantaneous dynamic knee angle assessment. Thus, the El-Gon may be a practical alternative to motion analysis for the assessment of countermovement jump and landing knee angles.

The validity and reliability of knee angles assessed by El-Gon has been investigated but its application has been limited to gait, dance and occupational movements. Specifically, the El-Gon displayed mean knee flexion angle differences of 1.0-1.2 degrees compared to motion analysis, with reliability coefficients of  $r = 0.93-0.95$  [10, 11]. Thus for relatively slow, sagittal plane movements, the El-Gon provides accurate and precise data.

The El-Gon has been used extensively to assess knee flexion angle during CMJ take-off [12-14] and landing movements [15, 16], despite the lack of any accuracy or precision measures. Therefore, the purpose of this study was to assess the validity and reliability of the El-Gon during the CMJ and landing using 2D video as the standard for comparison.

## 2 Methods

Twenty-two recreationally active men and women (12 female and 10 male; mean  $\pm$  SD; age =  $21.1 \pm 0.9$  years; height =  $170.7 \pm 9.7$  cm; body mass =  $73.0 \pm 17.8$  kg; jump height  $24.2 \pm 5.4$  cm) participated in this study. Inclusion criteria required subjects to be between 18-30 years old, without orthopedic lower limb or known cardiovascular pathology and without contraindications to exercise. All subjects provided informed consent and the study was approved by the institutional review board.

### 2.1 Experimental Design

Following a dynamic warm up, subjects performed 3 trials of the countermovement jump on a force platform (OR6-5-2000, AMTI, Watertown, MA, USA). One minute rest was provided between each jump. Video analysis of the jumps was obtained at 600 Hz (Exilim EX-F1, Casio Computer Co. LTD, Tokyo, Japan) from the sagittal plane using 2 cm diameter markers placed on the knee joint line, and estimated femur and tibia center of mass (Fig. 1). Markers were digitized using automatic digitizing software (MaxTRAQ 2D, Innovision Systems Inc, Columbiaville, MI, USA). An El-Gon (SG150, Biometrics Ltd., VA, USA), was positioned so the end blocks lined up with the tibia and thigh with the axis at the knee joint, and taped to maintain consistency between the angle measured by the El-Gon (Fig. 1). The endblocks of the El-Gon were attached to custom fabricated polyvinyl chloride extensions to reduce the skin movement as previously recommended by Rowe, et al. [17]. The El-Gon had a manufacturer reported accuracy of  $\pm 2^\circ$  over  $\pm 90^\circ$  and repeatability of  $1^\circ$  over the range of  $90^\circ$  [18]. El-Gon and force data were acquired through AcqKnowledge 3.9.1 software (Biopac Systems, CA, USA). The video and El-Gon were temporally synchronized using

an external trigger that elicited a square wave to the AcqKnowledge software and LED signal. Post-processing consisted of applying a fourth-order zero-lag Butterworth filter with a 20 Hz cut-off frequency to smooth the video and El-Gon data. A custom MATLAB (Mathworks Inc., Natick, MA, USA) program was used to reduce and process all data prior to statistical analysis.

## 2.2 Statistical Analysis

Cumulative error between video and El-Gon CMJ knee angle curves (continuous angles) were assessed by root mean square error ( $RMSE = \sqrt{((\text{video}-\text{El-Gon})^2 / \text{number of data points})}$ ). Three discrete angles were chosen for analysis and included: countermovement depth, angle at peak ground reaction force and landing angle (Figure 2). The countermovement depth was defined as the maximum angle during the initial descent phase of the countermovement. The angle at peak ground reaction force was defined as the angle at maximum vertical ground reaction force. Finally, the landing angle was defined as the angle corresponding to when the thigh marker was at the lowest position.

Total error between video and El-Gon knee angles at the three discrete time points was defined as the standard deviation of the mean difference scores. Agreement between video and El-Gon derived countermovement depth and landing knee flexion angle and angle at maximum vertical ground reaction force were assessed by a one-way ANOVA, Pearson product moment correlation and Bland-Altman methods of agreement [19]. Limits of agreement were calculated based on the repeated measurements [20]. El-Gon reliability of the three trials was assessed using a repeated measures ANOVA with a post-hoc Bonferroni correction and Intra-class correlation coefficient (ICC) on the discrete knee angles. Additionally, relative precision was calculated as the average within subject

RMSE standard deviation with 95% confidence interval. This value assesses instrumentation error independent of subject performance variation throughout the trials because in theory, the RMSE should stay the same throughout all the trials regardless of the subjects' jumping technique. All data were normally distributed [21]. White's test for heteroscedasticity was negative for all data ( $p > 0.05$ ). All statistical analyses were completed using SPSS 18.0 (SPSS Inc., Chicago, IL, USA). Significance level was set at  $p \leq 0.05$ .

### **3 Results**

The average error determined by RMSE of the El-Gon derived knee angles throughout the entire movement was  $7.03 \pm 2.69^\circ$  per data point. As shown in Table 1, countermovement depth, angle at maximum vertical ground reaction force and landing angle were 12.0, 5.7, and  $10.9^\circ$  higher, respectively, when assessed using an El-Gon ( $p < 0.001$ ). A Bland-Altman plot of all discrete knee angle measures revealed substantial non-systematic bias with a significant ( $p < 0.05$ ) regression line (Fig. 3). Figure 4 also displays the relationship between video and El-Gon derived knee angles with associated  $R^2$  values for each discrete knee angle measurement. Figure 5 displays the mean differences between the instruments throughout the entire movement. Similar reliability was found between video and El-Gon derived knee angles (Table 2). However, significant differences in RMSE between the two instruments were found between trials 1 and 3 ( $p = 0.019$ ). The average standard deviation of the within subject RMSE was  $0.83^\circ$  (95% Confidence Interval =  $0.53 - 1.13^\circ$ ).

#### 4 Discussion

The current study compared CMJ and landing knee angles obtained by video analysis and electrogoniometry. The El-Gon displayed total errors of 5.1, 3.2, and 4.7° compared to video analysis for the maximum countermovement knee angle, landing knee angle, and angle at maximum vertical ground reaction force, respectively. The present differences between El-Gon and video were higher than previously reported during walking movements [11]. The magnitude of differences between El-Gon and video derived knee angles became larger with increasing knee angles. The El-Gon displayed high precision albeit with lower accuracy compared to video methods.

This was the first study to assess the reliability of the El-Gon to assess knee angles during a countermovement jump and landing task. The El-Gon demonstrated excellent reliability at the various discrete time points [22]. Similar ICC values have been displayed for El-Gon derived knee angles during dancing and movements associated with gait [11, 23]. In the current study, small RMSE differences between trials 1 and 3 were found (0.8°), likely due to the attachment method of the El-Gon. More specifically, the El-Gon could have shifted under the tape during the relatively large countermovement depth angle or high acceleration landing phase. Relative precision was 0.83° with the 95% confidence interval of 0.53-1.13 °, which is similar to manufacturer, reported repeatability of 1°. If the El-Gon is used in a clinical setting to assess change in knee angle following an intervention or over repeated measurements a change in angle of less than 1.13° is likely to be insignificant and due to instrumentation error. The small relative error and similar reliability values compared to video techniques indicates the El-Gon provides repeatable data during dynamic movements. The findings of the current

study demonstrate the El-Gon has sufficient precision for research or clinical applications. Cross-talk compensation, proper sensor and axis alignment and calibration may increase the accuracy of the El-Gon [24].

Thirty degrees of rotation at the knee joint has been reported during the countermovement and landing points during jumping [25], which was likely a cause of El-Gon cross-talk errors and present differences between video and El-Gon knee angles. Sato and colleagues [24] found errors between 4 and 12° over angles of 60 and 100°, respectively, when El-Gon endblock rotations of 30 degrees were present. Additionally, the rotational motion at the knee joint increases with higher degrees of flexion and in the present study, higher El-Gon errors were reported at higher flexion angles, thus rotational cross-talk error could have led to the present differences between video and El-Gon derived knee angles. Manufacturers should consider including another channel for rotational movements or include a torsionmeter in the design to account for all cross-talk and movements in three dimensions [26, 27]. In addition to rotational cross-talk, individual sensor cross-talk or characteristics may have influenced the present discrepancies between knee angle assessment methods.

Individual cross-talk is based on the specific El-Gon manufacturer characteristics and may vary between instruments from the same manufacturer. Specifically, Sato and colleagues [27] found errors ranging from 1.75-10.1° between six biaxial El-Gons from the same manufacturer. Thus, users should be cautioned and aware of the variability between instruments even of the same make and model. To determine the error a “fingerprint” is produced which is determined by moving the El-Gon through a range of motion in one sole plane and investigating the data in the other “unaffected” plane. A

fingerprint of the current El-Gon was completed (Fig. 5), and revealed that a biologically feasible valgus/varus angle of around  $\pm 20^\circ$  [25, 28] influenced the “fixed” flexion/extension angles at 0 and  $90^\circ$ . A valgus angle or alignment is common during jumping [28] which likely influenced the El-Gon to overestimate the knee angles compared to video. Also, a hysteresis effect was displayed in both fingerprints (Fig. 6) which is common with this specific El-Gon [17].

The additional discrepancies between video and El-Gon angle determination could also have been due to, knee axis determination and digitizing error associated with two dimensional analysis. In the current study, the knee joint was modeled as a fixed axis hinge joint for the video technique whereas the El-Gon calculated angles based on a variable axis as described by Legnani et al. [26]. Figure 7 displays the theoretical differences between angles when the axis is fixed (video) and variable (El-Gon). The present error associated with digitizing, assessed by applying a maximum of 2cm (marker diameter) random error to each marker on each subject, was  $0.85 \pm 0.12^\circ$  per data point. This degree of error is well within normal error associated with automatic digitizing [30] and video knee angles displayed excellent reliability with low within subject variation.

Overall, the El-Gon overestimated the knee angles compared to video methods. However, the El-Gon displayed excellent reliability with precision values similar to manufacturer reports. The present knee angle differences between El-Gon and video may be explained by cross-talk errors and axis location.

## **5 Conclusion**

The researcher and/or clinician may use the El-Gon for the assessment of knee angle during jumping if specific recommendations are followed. The researcher should test

each El-Gon to obtain calibration/sensitivity characteristics similar to how this is done with other instruments such as force platforms, in order to correct for cross-talk errors. Additionally, torsiometer endblocks should be connected to bi-axial El-Gon endblocks to quantify and correct for rotational cross-talk errors. Further research is needed to quantify and correct for soft tissue artifact when using an El-Gon . For example, relationships should be established to assess the effect of soft tissue composition on El-Gon motion artifact. These procedures would be hard to follow/implement in a clinical setting therefore other recommendations can be made to the clinician to increase the accuracy and precision of El-Gon derived knee angles.

In a clinical setting, knee angle is likely assessed before and after a treatment intervention. To accurately and precisely assess the change in knee angle, proper attachment of the El-Gon is of utmost importance. First, the El-Gon should have extensions adhered to the endblocks to better mimic or contour to the long thigh and shank segments. Double sided tape should be applied to the extensions and taped to the skin as well as taped around the segments using elastic tape, to ensure minimal shifting. Additionally, the El-Gon should be properly aligned to the lower leg to reduce valgus/varus misalignments and ensure proper rotation about the knee joint axis. If countermovement knee angle, maximum landing knee angle and angle at maximum ground reaction force are assessed using electrogoniometry, the slope and intercept values (Table 1) can be used to compare to video assessment methods. Additionally, repeatability values between  $0.53\text{-}1.13^\circ$  can be assumed when using the El-Gon to assess knee angle during jumping and landing. The El-Gon can be a cost effective and time

efficient alternative to video analysis if the error is accounted for and attention is directed to proper alignment and attachment.

**Table 1** Video and El-Gon agreement and error measures for discrete and continuous knee angles (N=22).

	<i>Countermovement Depth (°)</i>	<i>Angle at Max GRF (°)</i>	<i>Landing Angle (°)</i>
Video Mean $\pm$ SD *	83.4 $\pm$ 7.7	38.6 $\pm$ 7.4	66.8 $\pm$ 10.1
El-Gon Mean $\pm$ SD	95.4 $\pm$ 10.0	44.3 $\pm$ 8.7	77.7 $\pm$ 12.8
Standard Error of Estimate	3.9	2.7	3.5
Regression Slope ( $\pm$ CI)	19.6 (17.0)	3.5 (6.4)	9.0 (9.7)
Regression Y-Int ( $\pm$ CI)	0.7 (0.2)	0.8 (0.1)	0.7 (0.1)
Mean Bias $\pm$ CI	12.0 $\pm$ 2.2	5.7 $\pm$ 1.4	10.9 $\pm$ 2.1
Total Error	5.1	3.2	4.7
95% Limits of Agreement	10.5	7.1	9.8
	<i>Trials</i>		
	1 <sup>#</sup>	2	3
RMSE $\pm$ SD	6.6 $\pm$ 2.4	7.1 $\pm$ 3.1	7.4 $\pm$ 2.9

Max= Maximum; GRF=Ground Reaction Force; El-Gon=Electrogoniometer; SD=Standard Deviation; Y-Int=y intercept CI= 95% Confidence Interval; SEM=Standard error of the mean; RMSE= Root mean square error; \* Sig Diff from El-Gon; <sup>#</sup> Sig Diff from trial 3

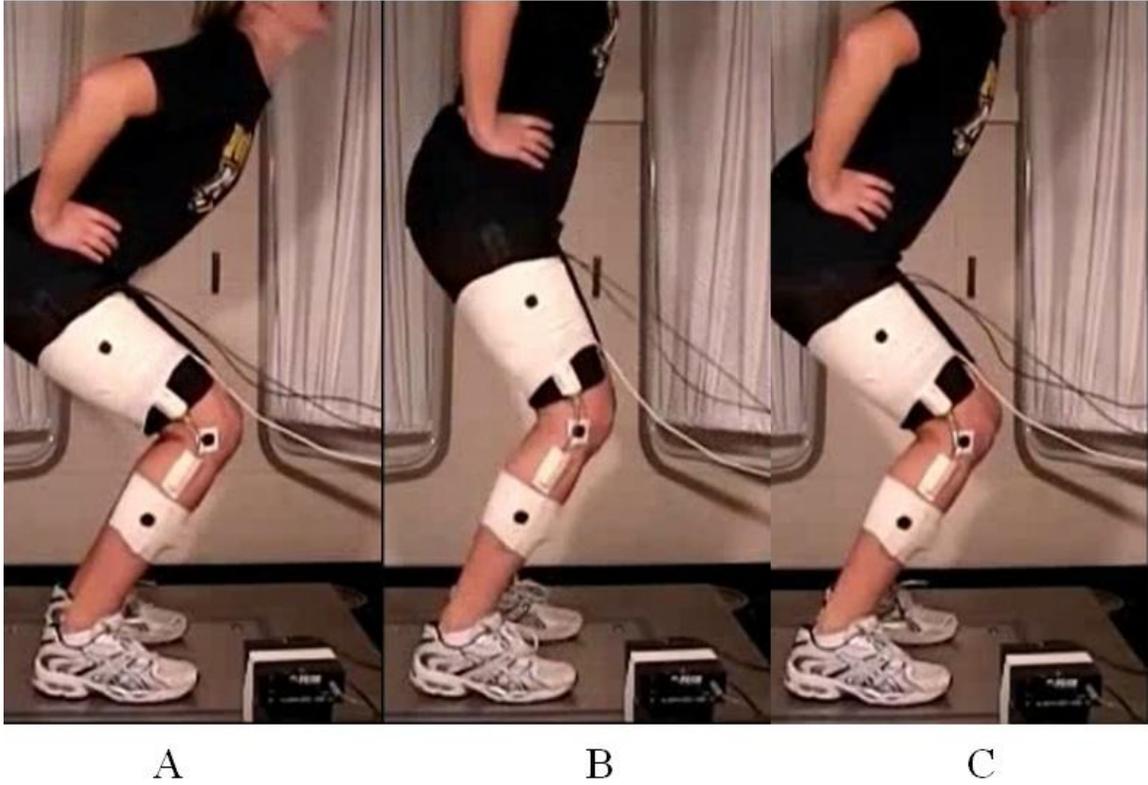
**Table 2** Video and El-Gon reliability measures\* (N=22).

	<i>Countermovement Depth</i>	<i>Angle at Max GRF</i>	<i>Landing Angle</i>
Video Intra-Subject Typical Error (°)	3.73	2.96	4.78
El-Gon Intra-Subject Typical Error (°)	3.81	3.54	5.75
Video ICC <sub>avg</sub> (95% CI)	0.89 (0.77-0.95)	0.92 (0.83-0.96)	0.90 (0.79-0.95)
El-Gon ICC <sub>avg</sub> (95% CI)	0.94 (0.88-0.97)	0.92 (0.83-0.96)	0.91(0.82-0.96)

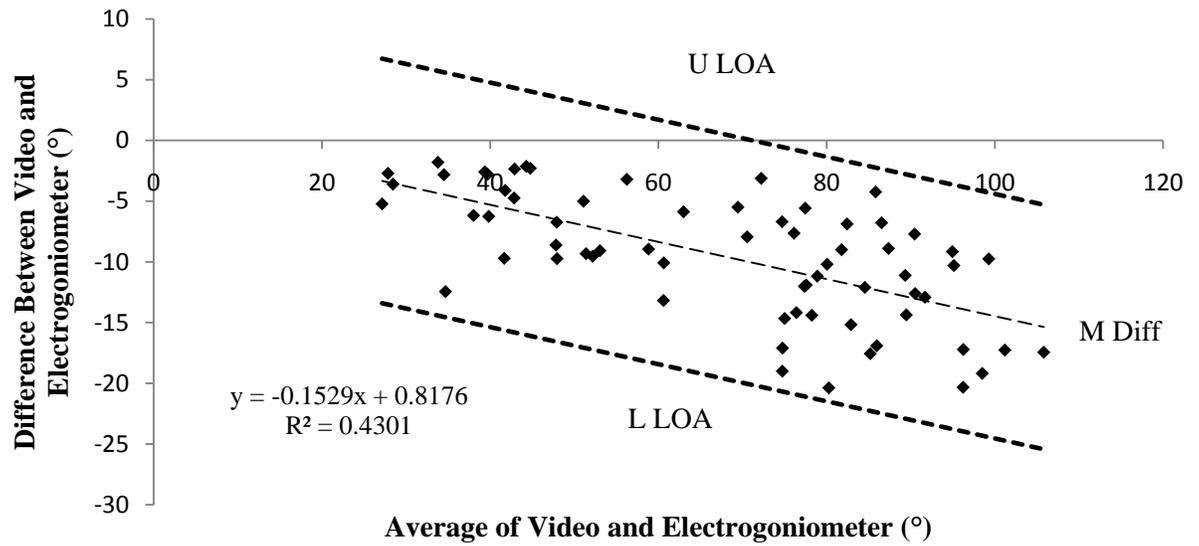
\* No differences between any of the trials were found for any of the discrete variables or instruments (p>0.05); Max=Maximum; GRF=Ground Reaction Force; El-Gon=Electrogoniometer; CI=Confidence Interval



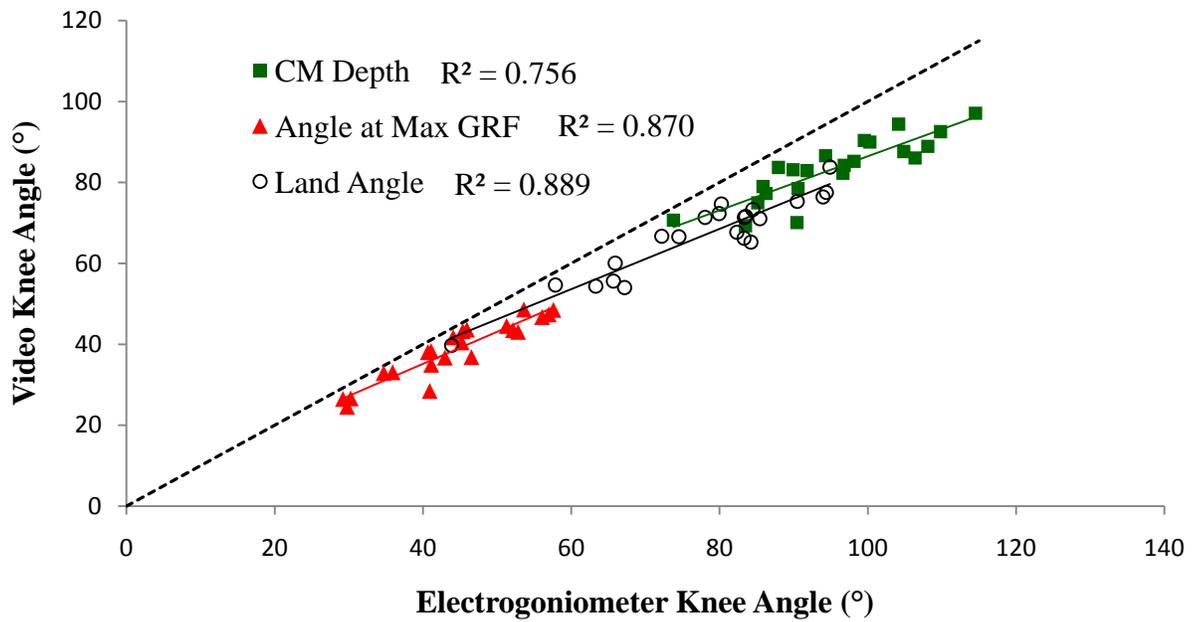
**Fig. 1** Markers (black dots) and El-Gon (arrow) placement.



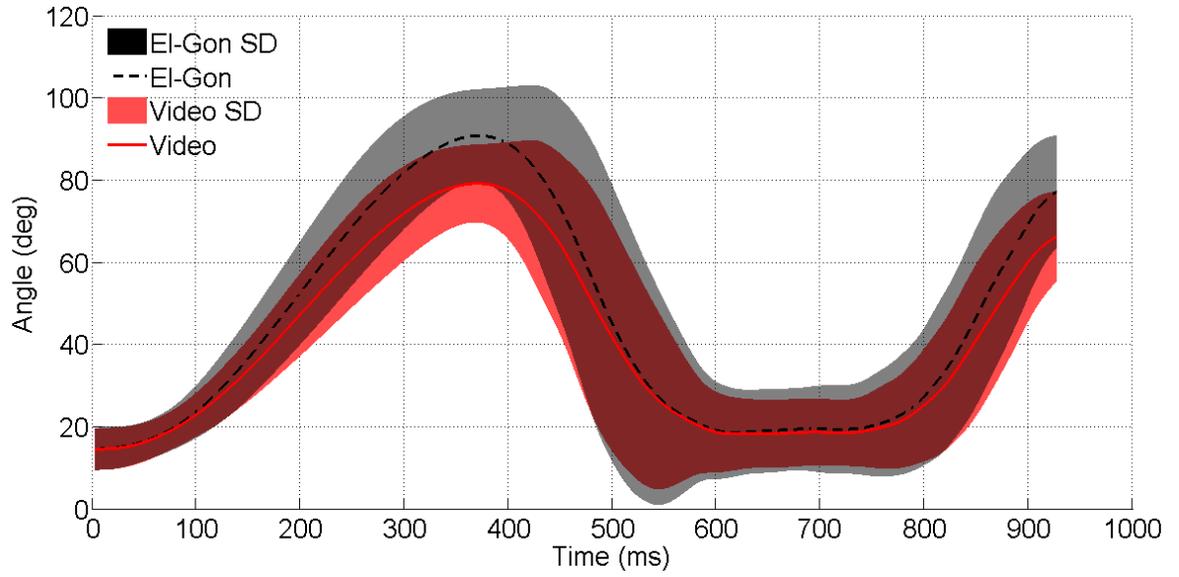
**Fig. 2** Discrete knee angles of interest: (A) Countermovement depth; (B) Angle at peak ground reaction force; (C) Landing angle



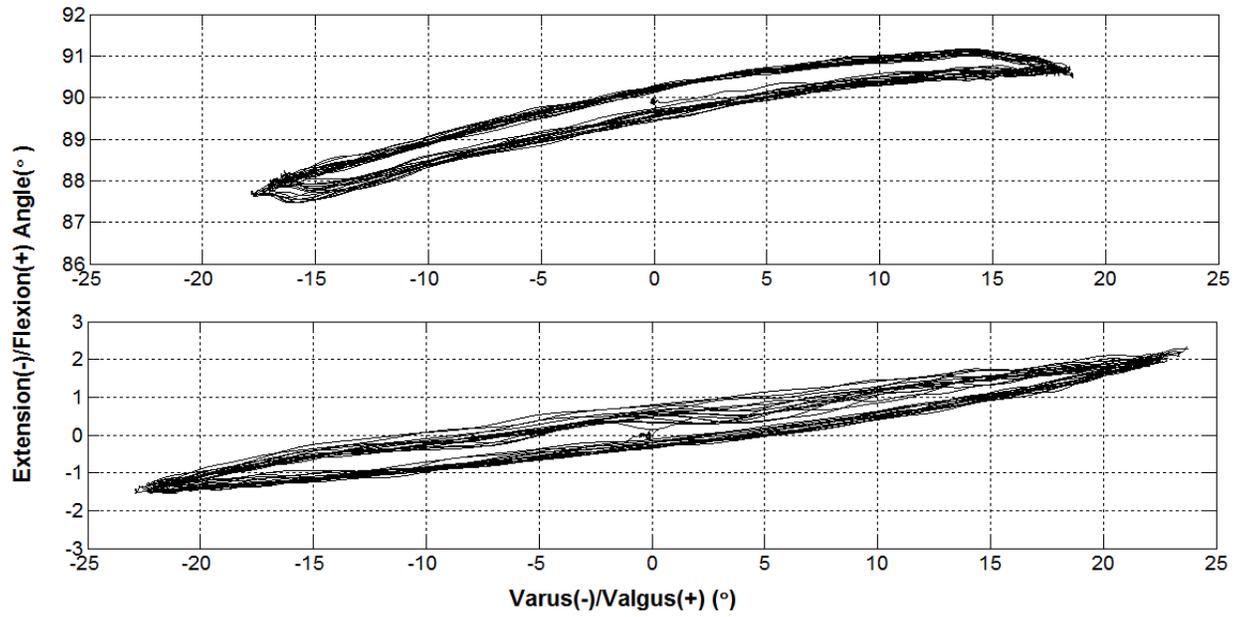
**Fig. 3** Bland-Altman plot of all average discrete knee angles measured by video and electrogoniometry (N=22). Significant non-systematic bias was displayed and confirmed by a significant regression ( $p < 0.05$ ). U LOA=Upper limit of agreement; M Diff=Mean difference; L LOA=Lower limit of agreement.



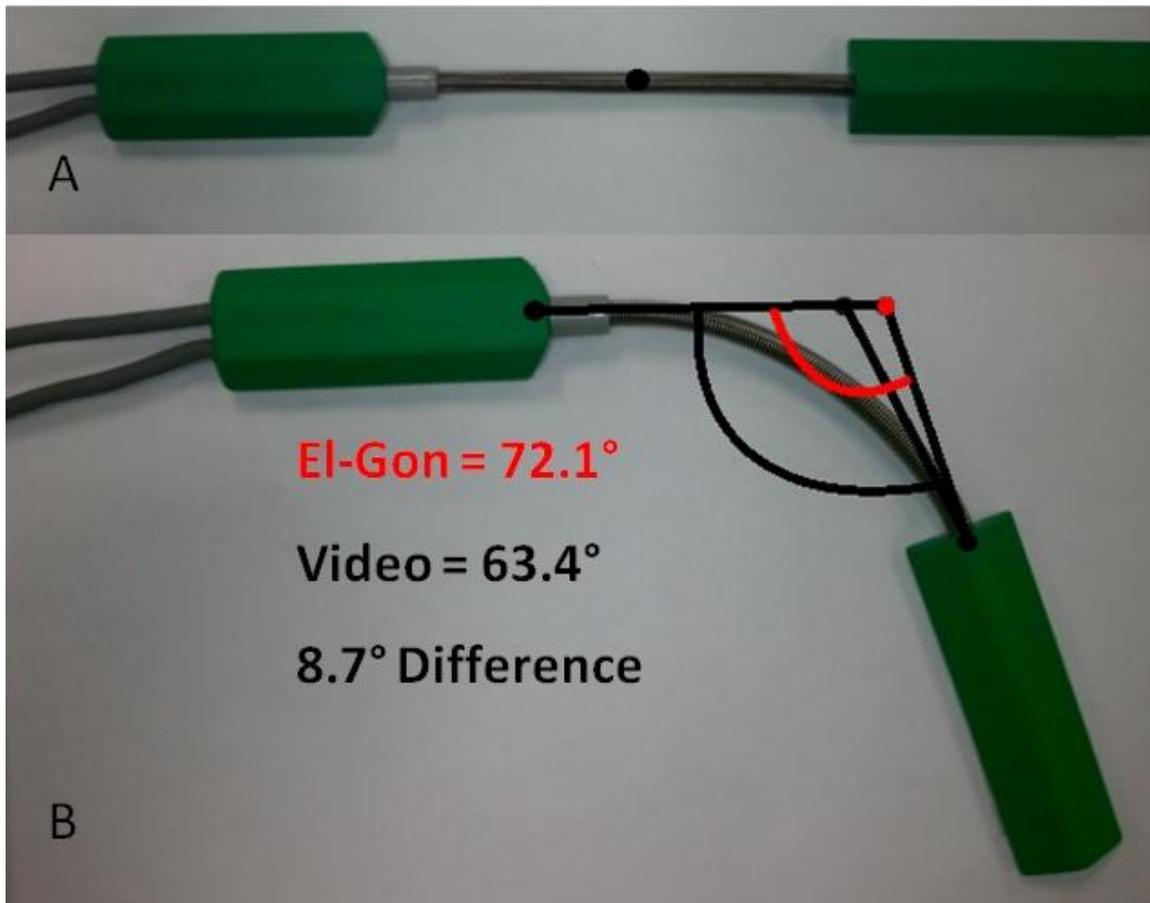
**Fig. 4** Regression analysis of all average discrete knee angles measured by video and electrogoniometry (N=22). Dashed line=perfect agreement; solid lines= significant linear regression ( $p < 0.05$ ).



**Fig. 5** Ensemble average knee angle curves during the countermovement jump assessed via video and electrogoniometry. El-Gon= electrogoniometry; SD=standard deviation.



**Fig. 6** Cross-talk (fingerprint) recorded during 60 seconds (about 15 cycles) of  $\pm 20^\circ$  of pure valgus/varus motion at fixed  $90^\circ$  (top) and  $0^\circ$  (bottom) flexion in a jig.



**Fig. 7** The effect of variable (El-Gon) vs. fixed (video) axis on angle calculation. A=initial position where the El-Gon and video has the same axis; B=final position where video axis (black) remains unchanged while El-Gon axis (red) moves.

## II. REVIEW OF THE LITERATURE

This review critically evaluates the importance of and methods quantifying knee joint angle during dynamic movements such as jumping and landing. Additionally, proper statistical techniques used to assess agreement between two methods will be addressed and discussed in detail.

### IMPORTANCE OF KNEE ANGLE QUANTIFICATION

#### *Prevalence of knee injury*

Over the last 30 years in the United States, high school and college sport participation has increased substantially. Specifically, female sport participation has increased by 78% and males by 25% [31, 32]. This increase in sport participation has resulted in a greater number of sports related injuries. Using the Injury Surveillance System, Hootman and colleagues [33], found that the injury rates remained unchanged since 1988 despite increases in injury prevention research [33]. They also found that the lower extremity is at the highest risk for injury compared to all other regions. Of the various lower extremity injuries Hootman et al.[33] also reported that the ankle and knee accounted for most of the lower extremity injuries. In particular, ankle sprains and anterior cruciate ligament (ACL) tears accounted for 15% and 3-5%, respectively, of all injuries [33]. ACL injury, however, is more expensive to treat and resulted in a substantially greater time away from sport compared to ankle sprains. ACL injuries are also likely to result in future complications including, increase occurrence of re-injury,

osteoarthritis, and other musculoskeletal pathologies [34]. Musculoskeletal overuse injuries of the knee, such as patellar tendonitis, are extremely common especially in volleyball [35]. Specifically, Ferretti and colleagues [35] reported that 28% of all injuries in volleyball were patellar tendonitis. Thus, the magnitude of incidences and severity of both acute and chronic knee injuries justifies particular emphasis in prevention efforts in these areas.

To prevent injuries and improve performance, screening processes should be developed and implemented for many athletes. Thus, to be time efficient, practitioners/clinicians must be reductionistic and choose a small number of variables to assess injury risk and performance. The countermovement jump test with concurrent knee angle assessment would provide the athlete with important information regarding both injury risk and performance and is easy to perform and quantify.

#### *Knee flexion angle and its association to injury*

The knee angle during landing from a jump influences the forces transmitted throughout the body's tissues. When excessive, these impact forces have been associated with various knee injuries, including tendinitis, anterior cruciate ligament (ACL) injury, and osteoarthritis [2, 7]. Knee flexion angle during jump landing significantly predicted patellar tendinitis in volleyball athletes [8] as well as aided in the prediction of ACL injury in high school female athletes [9]. It should be noted that ACL and other knee injuries are multifactorial in nature and knee flexion angle alone cannot predict injury risk [36], however this variable is relatively easy to quantify and manipulate with training and feedback [37] thus assessing knee flexion angle is one tool among many used to assess injury risk [9].

### *Knee flexion angle and its association with performance*

Knee flexion angle during the countermovement jump (CMJ) take-off phase influences jump performance. Jump height, is a variable used to assess lower body power and important for the success in many sports including basketball and volleyball [1]. Choosing the optimal knee joint angle during the countermovement phase has a significant effect on jump performance [2, 3]. Thus, quantifying knee joint angle during jumping has performance implications. Assessing knee joint angle during the CMJ also provides information regarding adaptations manifested through various training techniques [5, 38]. In particular, an increase in knee flexion angle following Olympic style weightlifting training resulted in improved jump performance whereas plyometric training resulted in improved jump height but with a concomitant decrease in knee angle [38]. These results may provide insight into how specific training regimes influence stretch shortening cycle function and/or eccentric phase adaptations. Assessing knee joint angle during the CMJ is important for athletics but also provides information regarding adolescent motor development.

The CMJ is a fundamental motor pattern that many adolescents use in various sports and play [39]. As children mature, jumping actions become less variable and more effective. Based on knee angle data during the CMJ, many children were correctly classified into various developmental stages [6]. Specifically, the maximum depth of the countermovement was highly variable and inconsistent in early “stage 1” subjects. This objective approach to quantify motor development has further application to cross-sectional and longitudinal analysis of motor development in both non-pathologic and pathologic populations.

Quantifying knee joint angle during the CMJ has many applications. Thus, choosing an instrument that is accurate, precise, inexpensive, easy to use and portable is important for practitioners and researchers assessing knee angle.

## **KNEE ANGLE ASSESSMENT INSTRUMENTS**

### *Two-Dimensional Digital Video Motion Capture*

The most common means of assessing motion of body segments or points is through motion capture technology [40]. The specific mathematical properties or theories on which motion capture technology are based, is detailed elsewhere [41]. Many types of motion capture systems exist including: video, infrared, and electromagnetic, using either passive markers or active light-emitting diodes. The most basic and inexpensive two-dimensional (2D) system consists of one digital video camera (~\$150) and markers. In short, the markers are placed on anatomically relevant body landmarks, which are then manually or automatically digitized (locating the center of the marker which corresponds to a specific pixel in the image). A scaling or calibration factor, based on a calibration frame or object with known distances, is used to transform the pixels into position units such as millimeters. The marker position can then be used to calculate relative or absolute joint angles.

Using 2D video to assess CMJ knee angle has both positive and negative qualities. Video analysis is affordable and portable. A video camera can be taken into any athletic or clinical setting and used. The first question, however, must be: does 2D video provide valid knee angles during jumping? To the author's knowledge, this question has yet to be answered but inferences from biomechanical gait analysis can aid in answering

this question. The one major problem with video analysis and skin mounted markers is skin movement artifact [42, 24]. Despite the ongoing debate on the magnitude of differences produced from skin and bone mounted markers, the error produced from skin movement during running was less than 5 degrees for knee flexion and was reliable within the same subject [42]. Thus, the non-invasive “gold standard” for dynamic knee joint angle quantification would then be three-dimensional (3D) video analysis [42]. Because the knee has six degrees of freedom (movement in all 3 planes) movement should be modeled in 3D. However, Myer and colleagues [9] found excellent association ( $r=0.95$ ) between 2D and 3D knee flexion range of motion values during depth jumps. Thus, 2D video analysis may be used to validly assess knee flexion angle during jumping. Video analysis, on the other hand, does have major drawbacks including; timely data analysis and requires moderate user knowledge.

Following video recording of the subjects, marker data has to be digitized, converted to positions, and angles must be calculated. With expensive automatic digitizing programs (~\$2,500) and high quality video feeds this can be completed in a relatively short (~15 minutes) time. With the free video analysis programs (Image J and MaxTraq 2D) this process can take up to 40 minutes per trial with only 3 markers, which is the minimum number of markers to quantify knee angle. Additionally, the marker data from the free digitizing programs would likely need to be exported into a different program (Excel or MATLAB) to calculate the joint angles based on the position data [41]. The use of the digitizing and calculation programs may require a moderate amount of knowledge. Thus, the main drawback to 2D video analysis is time, both analyzing the

data and learning the programs. Flexible electrogoniometry (El-Gon) is another simple and affordable alternative for quantifying joint angles at the knee.

### *Electrogoniometry*

Common flexible El-Gon's (i.e. Biometrics) quantify instantaneous joint angle in two planes, making this instrument time efficient. Briefly, the El-Gon determines knee angle by assessing the bend or strain in the flexible cable between the two endblocks. The relative angle between the two endblocks is proportional to the electrical strain in the cable, thus when calibrated to known angles, precise and valid angles are produced [24]. To date, no study has assessed the validity and reliability of electrogoniometer determined knee angles during jumping movements. However, electrogoniometer derived knee flexion has been compared to video analysis during walking and dancing movements. Results revealed high correlation ( $r > 0.9$ ), high reliability ( $ICC > 0.98$ ) and moderate concurrent validity (mean difference of 2-5°) to research based motion analysis systems [11, 17]. Electrogoniometers do however suffer from relatively large inter-instrument differences [25, 44] and cross-talk errors [22, 43, 45].

Considerable individual differences exist between El-Gons from the same manufacturer. Specifically, Sato and colleagues [25] found errors ranging from 1.75-10.1° between six biaxial El-Gons from the same manufacturer (Biometrics). This occurs most likely due to material and mechanical manufacturing variability. Thus, manufacturers should provide the users with a comprehensive “fingerprint” of the El-Gon throughout the full range of motion. Accuracy has been significantly improved when individual El-Gon differences have been assessed and compensated for by a precision “jig” and correction equations respectively [25, 45]. Another additional error with the El-

Gon results when a rotation is applied to the endblocks. This is called rotational cross-talk.

Rotational cross-talk would be an issue when assessing knee angle where considerable segment rotation is displayed during jumping. Sato and colleagues [22] found errors between 4 and 12° over angles of 60 and 100° of flexion, respectively, when El-Gon endblock rotations of 30 degrees were present. This amount of rotation is feasible and has been displayed during jumping [23]. Rotational crosstalk has also been significantly reduced (~13° reduction in error) when a fingerprint of the magnitude of crosstalk error was assessed in a precision jig. The cross-talk error may also be corrected for if a torsionmeter (which measures rotation) is used in conjunction with the El-Gon [45]. Thus, manufacturers should design a robust flexible tri-axial El-Gon or provide the user with a comprehensive fingerprint of each transducer to reduce the general and individual cross-talk error.

Despite relatively large inter-transducer errors, the established excellent reliability warrants the El-Gon's use to assess knee angle during a dynamic movement such as a CMJ. Since 2D video is a valid method of assessing knee angle during jumping, the El-Gon should be compared to 2D video to compare knee angle differences between the two methods. Proper statistical methods should be used to assess the agreement, which has recently been under debate [46].

### **ASSESSING AGREEMENT BETWEEN TWO INSTRUMENTS**

In order for an instrument to be valid or accurate and precise, the researcher must answer two questions: How repeatable are the measurements? and Do the methods measure the same criterion variable on average [19]? The first question pertains to

reliability and is discussed extensively elsewhere [47]. The second question is related to agreement. Many complex and simple statistical tools have been used to assess agreement in methods comparison studies including limits of agreement [19] and correlation and regression models [48]. The following section will discuss the benefits and drawbacks of using each method.

### *Limits of Agreement*

The Bland-Altman plot and associated 95% limits of agreement have been extensively used in methods comparison studies. The Bland-Altman plot displays the mean of the results between the two methods ( $(A+B)/2$ ) on the  $x$  axis and the  $y$  axis displays the difference between the two methods ( $(B-A)$ ). Additionally, 95% limits of agreement are calculated as the mean difference between the two methods (bias)  $\pm 1.96$  multiplied by the standard deviation of the differences. The viewer of the graph would interpret the limits of agreement as the expectation that 95% of the differences between measurements would lie between the limits [19].

Bland-Altman methods of agreement are rarely used in biomechanics disciplines [49]. Additionally, only one paper comparing El-Gon and video methods have employed Bland-Altman methods of agreement [30]. This paper, however, compared knee angular velocity as opposed to relative knee angle. A letter to the editor of the Journal of Biomechanics stated the importance of using Bland-Altman methods of agreement as opposed to correlation or regression [49]. Hopkins [46] however disagrees with this approach when assessing agreement between two methods and believes correlation coefficients and regression analysis should be used.

### *Correlation and regression models*

The basis for correlation and regression models for the application to methods comparison studies is to determine a calibration equation and then assess the agreement of the calibrated method. Hopkins [46] revealed that the Bland-Altman method indicated incorrectly that there were systematic biases in the relationship between two measures when one has been calibrated. Correlations and regression models are highly influenced by range of values [50]. For instance, if data are from a larger range, variables will appear more highly correlated. Likewise, including some extreme values to the dataset will also improve the correlation. Correlation is a measure of association, not agreement, thus large differences may be overlooked [50]. Ultimately, if a practical measure is used and compared to a “gold standard,” regression analysis will be beneficial if the investigator is looking to interchange the practical measure with the gold standard.

In the case of comparing knee angle assessed by El-Gon and 2D video, a “gold standard” is not technically present thus Bland-Altman methods would appropriately compare the instrumental biases. However, since researchers have used 2D video to assess knee angles correctly, calibration or regression equations may be beneficial when comparing studies using an El-Gon. Thus, a combination of statistical tools may be advantageous when assessing agreement between two practical measures.

### **Conclusion**

Video analysis and electrogoniometry are two practical tools used to assess knee angle during jump landings. The El-Gon, however, requires significantly less operating time and minimal user knowledge, making this instrument suitable for practitioners and

clinical use. Appropriate statistical tools should be used to compare the two instruments so decisions can be made on the validity and reliability of using such instrument in the sports or clinical setting. To determine if the El-Gon would be suitable for practical application, a Bland-Altman plot with limits of agreement and regression analysis would help determine the magnitude of differences between instruments and appropriate calibration if necessary. The El-Gon could then be used on a large scale in high schools or colleges as part of a pre-sports participation screening process to help identify athletes at risk for injury. The screening process is a very important component to the injury prevention model and by using a time efficient tool such as an El-Gon; injury rates may see a decline.

### III. CONCLUSIONS AND RECOMMENDATIONS

#### *Summary and Conclusions*

The present study sought to compare countermovement jump and landing knee angles obtained via video and flexible electrogoniometric analysis. For the current population of recreationally active college students, the electrogoniometer overestimated knee angles at various time points by an average of 7.03 degrees. The magnitude of differences increased with increasing knee angles. The differences are likely manifested in how the electrogoniometer obtains angles and the specific cross-talk characteristics of the sensor. If the specific cross-talk characteristics are taken into account and the El-Gon is precisely and properly attached to the subject, this sensor can be a time efficient and inexpensive tool to assess potential for injury risk and jump performance characteristics.

#### *Recommendations*

Since two dimensional motion analysis has some drawbacks, the current El-Gon should be validated with more precise three dimensional systems or intracortical bone pins. The latter, however, is likely too invasive to have any practical merit. Additionally, frontal plane knee angles (valgus/varus) are more important for determining ACL injury risk; thus, El-Gon varus/valgus angles should also be validated with three dimensional systems. In addition, a standardized precision jig should be engineered to properly assess and compensate for individual sensor cross-talk or the manufacturers should design a three dimensional electrogoniometer that is not subject to cross-talk error.

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## **APPENDICIES**

*APPENDIX A: Subject Consent Form*

NORTHERN MICHIGAN UNIVERSITY  
DEPARTMENT OF HPER

CONSENT TO ACT AS A HUMAN SUBJECT

Subject Name (print): \_\_\_\_\_ Date \_\_\_\_\_

1. I hereby volunteer to participate as a subject in exercise testing. I understand that this testing is part of a study entitled: "Validation of various instruments used to assess jumping performance and intensity." The purpose of the study is to compare a variety of instruments including accelerometers and electric goniometers to video analysis to determine jumping performance and intensity.

I hereby authorize Erich Petushek, William P. Ebben, Randall L. Jensen and/or assistants as may be selected by them to perform on me the following procedures:

(a) To have me perform five repetitions of vertical jumps. I will do each of these jumps on a force platform.

(b) I understand that I will have markers placed on my hip, knee, ankle, and at the base of my little toe.

These markers will be filmed with a video camera during the performance of the exercises and the data used to determine my knee and ankle angles and accelerations while jumping and landing. I will also have an electric goniometer attached to my knee and two accelerometers attached to my lower leg and foot to determine my knee angle and accelerations of my lower leg and foot, respectively.

2. The procedures outlined in paragraph 1 [above] have been explained to me.

3. I understand that the procedures described in paragraph 1 (above) involve the following risks and discomforts: temporary muscle pain and soreness is expected. However, I understand that I can terminate any test at any time at my discretion. Moreover, I should cease any test if I experience any abnormalities such as dizziness, light-headedness, or shortness of breath, etc.

4. I have been advised that the following benefits will be derived from my participation in this study: aside from the educational benefit of learning about plyometric testing or more instruction on the performance of the exercises, there are no direct benefits to me.

5. I understand that Erich Petushek, William P. Ebben, Randall L. Jensen and/or appropriate assistants as may be selected by them will answer any inquiries that I may have at any time concerning these procedures and/or investigations.

6. I understand that all data, concerning myself will be kept confidential and available only upon my written request. I further understand that in the event of publication, no association will be made between the reported data and myself.

7. I understand that there is no monetary compensation for my participation in this study.

8. I understand that in the event of physical injury directly resulting from participation, compensation cannot be provided.

9. I understand that I may terminate participation in this study at any time without prejudice to future care or any possible reimbursement of expenses, compensation, or employment status.

10. I understand that if I have any further questions regarding my rights as a participant in a research project I may contact Dr. Cynthia Prosen, Dean of Graduate Studies of Northern Michigan University (906-227-2300) [cprosen@nmu.edu](mailto:cprosen@nmu.edu). Any questions I have regarding the nature of this research project will be answered by Erich Petushek [erich.petushek@gmail.com](mailto:erich.petushek@gmail.com), William P. Ebben [webben70@hotmail.com](mailto:webben70@hotmail.com), or Dr. Randall Jensen (906-227-1184) [rajensen@nmu.edu](mailto:rajensen@nmu.edu).

Subject's Signature: \_\_\_\_\_

Witness: \_\_\_\_\_ Date: \_\_\_\_\_

## APPENDIX B: Physical Activity Readiness Questionnaire

Physical Activity Readiness  
Questionnaire - PAR-Q  
(revised 2002)

# PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
<input type="checkbox"/>	<input type="checkbox"/>	1. Has your doctor ever said that you have a heart condition <b>and</b> that you should only do physical activity recommended by a doctor?
<input type="checkbox"/>	<input type="checkbox"/>	2. Do you feel pain in your chest when you do physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	3. In the past month, have you had chest pain when you were not doing physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	4. Do you lose your balance because of dizziness or do you ever lose consciousness?
<input type="checkbox"/>	<input type="checkbox"/>	5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?
<input type="checkbox"/>	<input type="checkbox"/>	6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?
<input type="checkbox"/>	<input type="checkbox"/>	7. Do you know of <u>any other reason</u> why you should not do physical activity?

**If  
you  
answered**

### YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

### NO to all questions

- If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:
- start becoming much more physically active — begin slowly and build up gradually. This is the safest and easiest way to go.
  - take part in a fitness appraisal — this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

#### DELAY BECOMING MUCH MORE ACTIVE:

- If you are not feeling well because of a temporary illness such as a cold or a fever — wait until you feel better; or
- If you are or may be pregnant — talk to your doctor before you start becoming more active.

**PLEASE NOTE:** If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

**No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.**

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME \_\_\_\_\_

SIGNATURE \_\_\_\_\_

DATE \_\_\_\_\_

SIGNATURE OF PARENT  
or GUARDIAN (for participants under the age of majority) \_\_\_\_\_

WITNESS \_\_\_\_\_

**Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.**



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*APPENDIX C: Human Subjects Research Approval Letter*



Continuing Education  
1401 Presque Isle Avenue  
Marquette, MI 49855-5301

October 28, 2009

TO: Erich Petushek  
Nolan Jensen  
HPER

FROM: Cynthia A. Prosen, Ph.D.  
Dean of Graduate Studies & Research

RE: Human Subjects Proposal # HS09-298

Handwritten initials "CP" inside a circle, likely belonging to Cynthia A. Prosen.

"Validation of various instruments used to assess jumping performance and intensity"

The Internal Review Board (IRB) has reviewed your proposal and has given it final approval. To maintain permission from the Federal government to use human subjects in research, certain reporting processes are required. As the principal investigator, you are required to:

- A. Include the statement "Approved by IRB: Project # (listed above) on all research materials you distribute, as well as on any correspondence concerning this project.
- B. Provide the Internal Review Board letters from the agency(ies) where the research will take place within 14 days of the receipt of this letter. Letters from agencies should be submitted if the research is being done in (a) a hospital, in which case you will need a letter from the hospital administrator; (b) a school district, in which case you will need a letter from the superintendent, as well as the principal of the school where the research will be done; or (c) a facility that has its own Institutional Review Board, in which case you will need a letter from the chair of that board.
- C. Report to the Internal Review Board any deviations from the methods and procedures outlined in your original protocol. If you find that modifications of methods or procedures are necessary, please report these to the Human Subjects Research Review Committee before proceeding with data collection.
- D. Submit progress reports on your project every 12 months. You should report how many subjects have participated in the project and verify that you are following the methods and procedures outlined in your approved protocol.
- E. Report to the Internal Review Board that your project has been completed. You are required to provide a short progress report to the Internal Review Board in which you provide information about your subjects, procedures to ensure confidentiality/anonymity of subjects, and the final disposition of records obtained as part of the research (see Section II.C.7.c).
- F. Submit renewal of your project to the Internal Review Board if the project extends beyond three years from the date of approval.

It is your responsibility to seek renewal if you wish to continue with a three-year permit. At that time, you will complete (D) or (E), depending on the status of your project.

kjm

## APPENDIX D: Custom MATLAB Program

```
%This algorithm loads the files and calculates the knee angle based on
%video analysis and filters the elgon
%This also calculates the RMSE for the entire movement
clear all;
clc;

load('s18t1splined.txt','-ascii')
rawdata=s18t1splined;

t=rawdata(:,1);
Fz=rawdata(:,4);
goniflex=rawdata(:,9);
hipx=rawdata(:,10);
hipz=rawdata(:,11);
kneex=rawdata(:,12);
kneez=rawdata(:,13);
tibiax=rawdata(:,14);
tibiaz=rawdata(:,16);

count=size(rawdata,1);

plot(goniflex);

choice = menu('convert','yes','no')

if choice == 1;
    goniflex=goniflex.*-1;
end
%Butterworth Filter
fs=600; %sampling frequency
ts=1/fs;
fc=20;%cut off frequency for video and El-gon
Wc=tan(pi.*fc./fs);
k1=sqrt(2).*Wc;
k2=Wc.^2;
a0=k2./(1+k1+k2);
k3=(2.*a0)./k2;
a1=2.*a0;
a2=a0;
b0=(-2.*a0)+k3;
b1=1-(2.*a0)-k3;

hipx1st(1)=hipx(1);
hipx1st(2)=hipx(2);
hipx1st(3)=hipx(3);
hipx2nd(1)=hipx(1);
hipx2nd(2)=hipx(2);
hipz1st(1)=hipz(1);
hipz1st(2)=hipz(2);
hipz1st(3)=hipz(3);
hipz2nd(1)=hipz(1);
hipz2nd(2)=hipz(2);
```

```

kneex1st(1)=kneex(1);
kneex1st(2)=kneex(2);
kneex1st(3)=kneex(3);
kneex2nd(1)=kneex(1);
kneex2nd(2)=kneex(2);
kneez1st(1)=kneez(1);
kneez1st(2)=kneez(2);
kneez1st(3)=kneez(3);
kneez2nd(1)=kneez(1);
kneez2nd(2)=kneez(2);

tibiax1st(1)=tibiax(1);
tibiax1st(2)=tibiax(2);
tibiax1st(3)=tibiax(3);
tibiax2nd(1)=tibiax(1);
tibiax2nd(2)=tibiax(2);
tibiaz1st(1)=tibiaz(1);
tibiaz1st(2)=tibiaz(2);
tibiaz1st(3)=tibiaz(3);
tibiaz2nd(1)=tibiaz(1);
tibiaz2nd(2)=tibiaz(2);

goniflex1st(1)=goniflex(1);
goniflex1st(2)=goniflex(2);
goniflex1st(3)=goniflex(3);
goniflex2nd(1)=goniflex(1);
goniflex2nd(2)=goniflex(2);

%first pass
for i=3:count;
    hipx1st(i)=(a0.*hipx(i))+(a1.*hipx(i-1))+(a2.*hipx(i-2))+
(b0.*hipx(i-2))+(b1.*hipx(i-1));
    hipz1st(i)=(a0.*hipz(i))+(a1.*hipz(i-1))+(a2.*hipz(i-2))+
(b0.*hipz(i-2))+(b1.*hipz(i-1));
    kneex1st(i)=(a0.*kneex(i))+(a1.*kneex(i-1))+(a2.*kneex(i-2))+
(b0.*kneex(i-2))+(b1.*kneex(i-1));
    kneez1st(i)=(a0.*kneez(i))+(a1.*kneez(i-1))+(a2.*kneez(i-2))+
(b0.*kneez(i-2))+(b1.*kneez(i-1));
    tibiax1st(i)=(a0.*tibiax(i))+(a1.*tibiax(i-1))+(a2.*tibiax(i-2))+
(b0.*tibiax(i-2))+(b1.*tibiax(i-1));
    tibiaz1st(i)=(a0.*tibiaz(i))+(a1.*tibiaz(i-1))+(a2.*tibiaz(i-2))+
(b0.*tibiaz(i-2))+(b1.*tibiaz(i-1));
    goniflex1st(i)=(a0.*goniflex(i))+(a1.*goniflex(i-1))+(a2.*goniflex(i-2))+
(b0.*goniflex(i-2))+(b1.*goniflex(i-1));
end
hipx1st=hipx1st';
hipz1st=hipz1st';
kneex1st=kneex1st';
kneez1st=kneez1st';
tibiax1st=tibiax1st';
tibiaz1st=tibiaz1st';
goniflex1st=goniflex1st';
%second pass
for j=3:(count-2);

```

```

hipx2nd(j)=(a0.*hipx1st(j))+(a1.*hipx1st(j+1))+(a2.*hipx1st(j+2))+(b0.*
hipx2nd(j-1))+(b1.*hipx2nd(j-2));

hipz2nd(j)=(a0.*hipz1st(j))+(a1.*hipz1st(j+1))+(a2.*hipz1st(j+2))+(b0.*
hipz2nd(j-1))+(b1.*hipz2nd(j-2));

kneex2nd(j)=(a0.*kneex1st(j))+(a1.*kneex1st(j+1))+(a2.*kneex1st(j+2))+(
b0.*kneex2nd(j-1))+(b1.*kneex2nd(j-2));

kneez2nd(j)=(a0.*kneez1st(j))+(a1.*kneez1st(j+1))+(a2.*kneez1st(j+2))+(
b0.*kneez2nd(j-1))+(b1.*kneez2nd(j-2));

tibiax2nd(j)=(a0.*tibiax1st(j))+(a1.*tibiax1st(j+1))+(a2.*tibiax1st(j+2
))+ (b0.*tibiax2nd(j-1))+(b1.*tibiax2nd(j-2));

tibiaz2nd(j)=(a0.*tibiaz1st(j))+(a1.*tibiaz1st(j+1))+(a2.*tibiaz1st(j+2
))+ (b0.*tibiaz2nd(j-1))+(b1.*tibiaz2nd(j-2));

goniflex2nd(j)=(a0.*goniflex1st(j))+(a1.*goniflex1st(j+1))+(a2.*gonifle
x1st(j+2))+(b0.*goniflex2nd(j-1))+(b1.*goniflex2nd(j-2));

end;
hipx2nd=hipx2nd';
hipz2nd=hipz2nd';
kneex2nd=kneex2nd';
kneez2nd=kneez2nd';
tibiax2nd=tibiax2nd';
tibiaz2nd=tibiaz2nd';
goniflex2nd=goniflex2nd';
goniflexfilt=goniflex2nd;
%


---


%knee and tibia angle calculations using the filtered position
data
tibiaanglefilt=atand((kneez2nd-tibiaz2nd)./(kneex2nd-tibiax2nd));
tibiaangle2filt=90-atand((kneez2nd-tibiaz2nd)./(kneex2nd-tibiax2nd));
kneeanglefilt=(acos(((kneex2nd-tibiax2nd).*(hipx2nd-kneex2nd))...
+((kneez2nd-tibiaz2nd).*(hipz2nd-kneez2nd)))/...
((sqrt(((kneex2nd-tibiax2nd).^2)+((kneez2nd-tibiaz2nd).^2)))...
.*(sqrt(((hipx2nd-kneex2nd).^2)+((hipz2nd-kneez2nd).^2)))))...
.*57.295777951));

Fz2=Fz;
Fz2(count-2)=[];
Fz3=Fz2;
Fz3(count-2)=[];

t1=t;
t1(count-2)=[];
t2=t1;
t2(count-2)=[];

if goniflexfilt(1)>kneeanglefilt(1)
    goniflexfilt=goniflexfilt-(goniflexfilt(1)-kneeanglefilt(1));

```

```

else
    goniflexfilt=goniflexfilt+(kneeanglefilt(1)-goniflexfilt(1));
end

[vidpks, vpkt] = findpeaks(kneeanglefilt, 'MINPEAKHEIGHT', 40, 'NPEAKS', 2);
[gonipks, gpkt] = findpeaks(goniflexfilt, 'MINPEAKHEIGHT', 40, 'NPEAKS', 2);

if size(vidpks, 2) > 1
    if vidpks(2) > vidpks(1)
        vpkt1 = vpkt(2) * ts;
        vidpks1 = vidpks(2);
    elseif vidpks(1) > vidpks(2)
        vpkt1 = vpkt(1) * ts;
        vidpks1 = vidpks(1);
    end
else
    vpkt1 = vpkt(1) * ts;
    vidpks1 = vidpks(1);
end

if size(gonipks, 2) > 1
    if gonipks(2) > gonipks(1)
        gpkt1 = gpkt(2) * ts;
        gonipks1 = gonipks(2);
    elseif gonipks(1) > gonipks(2)
        gpkt1 = gpkt(1) * ts;
        gonipks1 = gonipks(1);
    end
else
    gpkt1 = gpkt(1) * ts;
    gonipks1 = gonipks(1);
end

data = [kneeanglefilt, goniflexfilt, Fz3];
[maxvid, maxvidt] = max(data(:, 1));
[maxgoni, maxgonit] = max(data(:, 2));
[maxFz, maxFzt] = max(data(:, 3));
values = [maxvid, maxgoni, maxFz];
indexes = ts .* ([maxvidt, maxgonit, maxFzt] - 1);
maxvid1 = num2str(values(:, 1));
maxgoni1 = num2str(values(:, 2));
maxFz1 = num2str(values(:, 3));
maxvid1t = num2str(indexes(:, 1));
maxgoni1t = num2str(indexes(:, 2));
maxFz1t = num2str(indexes(:, 3));

data = [kneeanglefilt, goniflexfilt, Fz3];
[maxFz, maxFzt] = max(data(:, 3));
values = [maxFz];
indexes = ts .* ([maxFzt] - 1);
maxFz1 = values(:, 1);
maxFz1t = indexes(:, 1);

landvid = kneeanglefilt(maxFzt);
landgoni = goniflexfilt(maxFzt);

dim = size(kneeanglefilt) / fs;

```

```

tnew=[ts:ts:dim]';

vidx=tnew(int16(vpkt1./ts));
gonix=tnew(int16(gpkt1./ts));

count3=size(kneeanglefilt);
landvidangmax=kneeanglefilt(count3(:,1));
landgoniangmax=goniflexfilt(count3(:,1));

%error analysis
error = (kneeanglefilt-goniflexfilt).^2;
RMSE = sqrt((sum(error))/length(error)); %RMS error

ans2 = [RMSE vidpks1 gonipks1 vpkt1 gpkt1 landvid landgoni ...
        landvidangmax landgoniangmax]
ans3 = [kneeanglefilt goniflexfilt Fz3];

figure
hold on
[AX,H1,H2] = plotyy(tnew,kneeanglefilt,tnew,Fz3);
set(H1,'LineStyle','--')
set(H2,'LineStyle','-')
title(['Ground Reaction Force and Knee Angle Relationship'])
xlabel('Time, t, (seconds)')
legend('Video Knee Angle','GRF')
legend('boxoff')
plot(tnew(maxFzt),landvid++1,'k*','markerfacecolor','black',...
      'markersize',10);
hold off

figure
hold on
plot(tnew,goniflexfilt,'k--');
plot(tnew,kneeanglefilt,'k-');
plot(vidx,vidpks1+1,'k^','markerfacecolor','Black','markersize',10);
plot(gonix,gonipks1+1,'k*','markerfacecolor','black','markersize',10);
plot(max(tnew),landvidangmax+1,'k^','markerfacecolor','black',...
      'markersize',10);
plot(max(tnew),landgoniangmax+1,'k*','markerfacecolor','black',...
      'markersize',10);
plot(tnew(maxFzt),landvid+1,'k^','markerfacecolor','Black',...
      'markersize',10);
plot(tnew(maxFzt),landgoni+1,'k*','markerfacecolor','black',...
      'markersize',10);
legend('El-Gon','Video')
title('Knee angle comparison')
xlabel('Time (s)');
ylabel('Angle (deg)');
hold off

```