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Discriminating Between Maximal, Submaximal and Feigned Isokinetic Shoulder Flexion and Extension Strength Efforts Using Frequency Content Analysis

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Abstract

Background: Assessments of muscular strength capabilities are routinely performed in the medico-legal setting for aiding in determination of impairment ratings, possible disability status and compensation following injury. However, a basic tenet in the use of strength scores is that maximal voluntary efforts were exerted during testing. There is a paucity of methods for ascertaining the exertion of such efforts during shoulder muscular testing. Therefore, the purpose of this investigation was to assess whether a novel measure, namely the isokinetic dynamometry- based moment signal's frequency content, may be used for purposes of differentiating between maximal, sincere sub-maximal and feigned shoulder flexion/extension efforts.

Methods: 27 participants performed 3 sets of 5 shoulder concentric flexion/extension repetitions through a 60° of range of motion at angular velocities of 30°sec-1 and 120°sec^{-1}. The sets consisted of maximal efforts, an attempt to feign muscular strength capabilities for financial gain, and a set of sincere submaximal efforts performed at a self-selected level. Moment data were transformed into the frequency domain using the Fast Fourier transform algorithm, and signal's frequency content contained within 95% and 99% of total signal power were extracted as outcome measures. Tolerance interval based cut-off scores were subsequently calculated to discriminate between maximal and non-maximal attempts.

Results: On average, maximal effort strength records exhibited lower frequency content than both feigned and sincere submaximal attempts. In terms of discriminatory performance, the best performing tolerance interval based cut-off scores meant of differentiating between maximal and non-maximal efforts yielded specificity and sensitivity values of 92.6% and 70.4%, and 100% and 72.2% for the low and high testing velocities, respectively.

Conclusion: The performance of the cut-off scores suggests that the moment signal's frequency content significantly contributes to the ability to differentiate between maximal and non-maximal efforts.

Keywords: Isokinetic, Sincerity of effort, Submaximal effort, Shoulder, Strength

Introduction

Background

Work-related injuries to the shoulder complex are common in the United States and Canada, and impose a significant burden in terms of time off work and related restitutions [1,2]. The evaluation of shoulder muscular strength may assist clinicians in assessing an injured worker's progression through rehabilitation, as well as may contribute to decision-making processes related to disability and impairment ratings, and readiness to return to work. Use of isokinetic dynamometry for such purposes may be advantageous due several factors, including: the ability to test several shoulder muscle groups (i.e. flexor and extensors, abductors and adductors, internal and external rotators), the ability to accommodate those that are injured by control of the range of motion, movement velocity and the contraction type at which efforts are performed, and lastly, due to the quantitative nature of the data output which allows for comprehensive analyses [3]. However, a prerequisite in the use of strength scores in the aforementioned settings relates to the exertion of maximal voluntary efforts during testing [3,4]. Thus, a necessity arises to devise methods for enabling clinicians to ascertain with a high degree of confidence whether maximal efforts were in fact produced.

A theoretical approach that may serve as a basis for development of methods draws from presumed differences in the neuromuscular strategies during performance of maximal or non-maximal efforts [5,6]. Specifically, during maximal voluntary effort attempts the neuromuscular strategy adopted by humans apparently aims to maximize motor unit rate recruitment and rate coding of the agonist muscles, while at the same time attempts to minimize antagonistic muscle activity. On the other hand, during performance of non-maximal efforts, central nervous system regulation of motor unit activation seems to vary in an attempt to modify the intended muscular force output to that actually exerted, as gauged by continuous peripheral feedback [5,6].

It can be inferred that these aforementioned theoretical differences in neuromuscular strategies between maximal and non-maximal efforts will be partly manifested in the degree of strength curve smoothness,

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which may be quantified using the strength curve's frequency content. This inference is supported by previous investigations who have described that a conspicuous feature of the maximal isokinetic strength curves is a high degree of moment steadiness, or smoothness through the tested range of motion [7-10]. On the other hand, during production of non-maximal efforts, strength curves display irregular patterns typified by the presence of high frequency oscillations [7-10]. This investigation, therefore, aimed at exploiting the strength curve's frequency content for establishing decision rules for differentiating between maximal and non-maximal concentric, flexion/extension shoulder musculature efforts.

Methods

Participants

Participants were recruited through direct contact and advertisement. A self-report questionnaire was used to identify exclusion criteria, including: current or past injury to the upper extremities and spine; recurrent episodes of fainting or dizziness; a history of high blood pressure and current use of medication (excluding contraceptives).

A total of 27 participants were included in the study. Of these, 15 were men (mean ± SD age 26.8 ± 3.2 years; mass 79 ± 10 kg; height 1.77 ± 0.06 m); and 12 were women (24.7 ± 3.1 years of age; mass 65 ± 5 kg.; height 1.68 ± 0.05 m). The participants had no prior experience exercising using isokinetic dynamometry. Each participant provided written informed consent prior to testing. The experimental procedures were approved by the Queen's University General Research Ethics Board.

Procedures

A Biodex System 3 isokinetic dynamometer (Biodex Medical Inc., Shirley, NY, USA) sampling at 100 Hz was used to test the strength of dominant shoulder's flexors and extensors muscle groups. Side dominance was defined as the preferred ball throwing arm. Verification of the dynamometer's calibration settings was done prior to testing.

Upon arrival to the laboratory, the participants performed examiner-guided arm rotations and stretching. Thereafter, the participants were seated and restrained using pelvis and chest straps, and using a strap crossing the untested shoulder. The tested shoulder's acromium process was then palpated and aligned with the dynamometer's axis of rotation. In three cases, the axis alignment procedure was not possible due to the combined effect of the participants' trunk length and the dynamometer's chair and motor height-adjustment reaching their minimal and maximal limits, respectively. In these cases, the chair height was set to its lowest level, whilst the motor was brought up to its maximal height.

Isokinetic warm-up and familiarization included performance of 6 sets of 3 low effort concentric repetitions starting at a testing velocity of 180°sec^{-1} and descending to 30°sec^{-1} in 30°sec^{-1} increments. Following 2-3 minutes of rest, the participants performed 1-2 warm-up repetitions at a self-perceived 80% and 90% of maximum, followed by 1-2 warm up repetitions each of the two testing velocities at maximal voluntary effort (MVE). The participants were instructed to neutrally grip the specialized shoulder attachment whilst maintaining an extended elbow position and to perform efforts through the entire range of motion without attempting to decelerate the lever arm at end-range.

Testing was performed through a 60° range of motion (ROM) corresponding to -20° of flexion to 40° of extension, with 0° signifying a horizontal arm position in the sagittal plane. The lower ROM limit was set as such since further shoulder extension was not possible due to the lever arm hitting the seat. The upper ROM value limit was determined mainly due to difficulties encountered by the participants in rotating the lever arm above this level. This difficulty may possibly be a consequence of the inherent misalignment between the mechanical and biological rotation axes being exacerbated when approaching full shoulder flexion.

Testing incorporated 3 sets of 5 continuous shoulder flexion and extension repetitions performed at velocities of 30°sec-1 and 120°sec^{-1}. The first set was of MVEs. The second set was of simulated feigned muscular effort attempts for the exclusive purpose of financial gain in a compensation setting [7,8]. The third set was of submaximal efforts performed at a self-selected, comfortable level. That is, the participants were free to choose the submaximal level of strength exerted during the 2nd set. Set order was not randomized since we wanted the participants to be fully aware of their maximal capabilities prior to performance of the non-maximal sets. The feigned set preceded the sincere, self-selected submaximal one since we did not want to consciously evoke within participants a feigning strategy that would resemble a sincere non-maximal attempt [7,8]. The participants were allowed to perform a self-selected number of practice repetitions preceding both non-maximal effort sets. During testing, the participants were allowed to view the concurrent moment-time series display, as well as received standardized audible feedback. Testing of the slower velocity always preceded the faster one and a 3- 4 minute rest period was provided in between sets [3].

Data Analysis

For descriptive purposes, we extracted each individual's gravity corrected peak moment (i.e. highest value within any repetition) for both flexion and extension efforts in each of the three sets. The peak moment values were subsequently expressed as percentages of maximal effort attempts.

The moment time series of the entire set consisted of an alternating waveform with a slight direct current (DC) bias towards the stronger side. Since the presence of this bias may result in the signal's frequency content being dependent on the relative strength of the extensor's and flexor's muscle groups, the bias was removed prior to calculations by subtraction from the entire moment waveform. Moment signals were then transformed into the frequency domain using Matlab's built-in fft function (v. 7.5, The MathWorks, Inc., Natick, MA), and the power spectrum was subsequently obtained. For each individual set, the power contained within 95% and 99% of total signal power was calculated [11,12].

Statistical Analysis

A mixed design, repeated measures analysis of variance ($\alpha \leq 0.05$) was performed to discern group differences in frequency content scores at each percentage of signal power level. For these tests, the between subject factor was participant sex and the within subject factor was effort type. We did not include speed as a within subject factor since the differences in the time series length would possibly render a comparison across speeds invalid due to different frequency resolutions. In addition, since we transformed the entire moment curve into the frequency domain, frequency content scores for flexion and extension directions were not available for this particular comparison.

Following an evaluation of the omnibus statistical test results, cut-off scores were established to differentiate between maximal and non-maximal efforts where the latter consisted of both sincere sub maximal and feigned attempts. The cut-off scores were established by calculation of one-sided tolerance intervals with normal distribution assumption at two levels: The first covered an estimated 95% of population maximal efforts with a probability of 95%, and the second covered 99% of population maximal efforts with a probability of 95% [13]. The use of two aforementioned population percentage estimates essentially allowed establishment of a lenient and more conservative cut-off score, respectively. The rationale for developing two cut-off scores was that this would allow for accommodation of the individual being tested and the consequences surrounding their assessment. In relation, the 95% level of confidence was chosen since it represents one that is commonly accepted as a minimum standard by scientific community. Note that that there are no clear guidelines pertaining to selection of population coverage percentages and levels of confidence for purposes such as those in the current investigation. The performance of the cut-offs are reported in terms of the number of misclassification per condition and accompanying specificity and sensitivity percentages.

Lastly, a mixed design, repeated measures analysis of variance ($\alpha \leq 0.05$) was performed to discern group differences in the percentage of effort exerted in the sincere and feigned effort sets across males and females, testing velocity and direction of effort (flexion/extension). Note that an arcsine transformation was applied to the percentage data prior to testing.

Results

A summary of the strength exerted during feigned and sincere non-maximal effort attempts expressed as a percentage of maximal efforts in presented in Table 1. There was a significant main effect of direction on the percentage of effort exerted during performance of the two non-maximal effort sets, $F(1,25)=50.727$, $p < 0.01$. Examination of values presented in Table 1 show that non-maximal shoulder flexion efforts were performed at approximately two thirds of MVE level, whilst shoulder extension efforts were performed at approximately half of MVE level. The effects of sex, contraction type (sincere or feigned) and testing speed did not exhibit statistically significant interactions or main effects.

Descriptive statistics of the frequency content obtained at each percentage of total signal power at each testing velocity are presented in Table 2. A significant main effect of contraction type was found for frequency content scores obtained during performance at 30°sec-1 at 95% of total signal power, $F(2,50)=16.804$, $p<0.01$, and at 99% of signal $F(2,50)=29.189$, $p<0.01$. Similarly, a significant main effect of contraction type was found for frequency content scores obtained during performance at 120°sec^{-1} at 95% of total signal power, $F(2,50)=42.643$, $p<0.01$, and at 99% of signal $F(2,50)=43.196$, $p<0.01$. There was no statistical effect of sex as a function of speed or percentage of signal power ($p>0.05$ in all cases).

Results of subsequent statistical contrasts between the three contractions performed at each speed showed that maximal efforts exhibited significantly lower frequency content than both sincere non-maximal and feigned efforts ($p<0.05$ in all cases). In addition, sincere non-maximal efforts exhibited lower frequency content than feigned attempts ($p<0.05$ in all cases). However, evaluation of the standard deviation and ranges of feigned effort scores show that these completely overlap with those performed sincerely. Based on these results, it was decided that clinically meaningful tolerance interval cut-off scores should be constructed with the intent of classifying efforts as being performed maximally. Similar cut-off scores for classifying efforts as being performed sincerely (or not) were not constructed since the these would obviously exhibit low classification performance given the severe score overlap. In addition, the lack of interaction or main effects pertaining to participant sex led to our decision to pool frequency content scores of both sexes in the construction of the cut-off scores. The cut-off scores meant to classify efforts as performed maximally or not are presented in Table 2, and their performance varies as function of the estimated population percentage coverage, as well as the percentage of total signal power considered. In particular, for efforts performed at 30°sec^{-1}, the best performing cut-off score yielded specificity and sensitivity values of 92.6% and 70.4%, respectively. For efforts performed at 120°sec^{-1}, the best performing cut-off score resulted in test sensitivity and specificity values of 100% and 72.2%, respectively. Of interest is that the number of feigned efforts misclassified as maximal is smaller than that of self-selected submaximal efforts at each testing velocity and percentage of signal power.

Discussion

The performance of the cut-off scores meant to ascertain maximal effort production during strength testing established in this investigation are comparable to those reported in other investigations utilizing a single time domain-measure based on static and dynamic exertions of various muscle groups [14-19]. However, the current results are slightly inferior to those developed specifically for the shoulder joint musculature [20-22]. Specifically, Chaler et al. [21] report that in participants with characteristics similar to the ones tested in this study, complete discrimination was achieved between maximal and feigned efforts attempts (i.e. 100% sensitivity and specificity values), whilst Dvir et al. [22] report an identification power ranging between 82.4% and 100%, dependent on the testing velocities and tolerance interval cut-off scores considered.

However, the current investigation's experimental design substantially differs from these aforementioned studies and in fact from the majority of previous investigations concerned with the topic of differentiating between maximal and non-maximal efforts. The major difference relates to the consideration of two types of non-maximal efforts (i.e. feigned and sincere) in cut- off score determination. It has been noted by previous investigators that several reasons may inhibit participants from exerting their maximal effort with no attempt to alter test results in a deceitful manner [3,4,23]. These reasons may include, for example, misunderstanding of instructions or of the importance of the test, as well as various psychological issues, such as fear of pain or injury, depression, and others [3,4,23]. Thus, a non-maximal effort may be exerted by an individual while not attempting to deceive the examiner into concluding a deficiency in muscular strength capabilities. This consequently requires the experimental design and development of decision rules to include performance of sincere submaximal and feigning attempts, a point that has been neglected in the vast majority of previous investigations [7]. Therefore, direct comparisons between the results of the current investigation and previous ones should be done with caution. In addition, as opposed to the vast majority of previous investigations concerned with differentiating between maximal and non-maximal efforts, feedback of performance was provided throughout testing. The reasoning for this relates to the positive effect feedback has been found to have on isokinetic muscular strength values [24-26]. The provision of feedback also concurs with at least one definition of what constitutes a maximal voluntary contraction: "a maximal contraction that a subject accepts as maximal and that is produced with appropriate continuous feedback of achievement" [27].

Direction	Velocity	Maximal Efforts	Feigned Efforts	Submaximal Efforts
Shoulder Flexion	**30°sec^{-1}**	100%	66% ± 20% (18% to 92%)	70% ± 14% (40% to 99%)
	120°sec^{-1}	100%	69% ± 20% (27% to 96%)	65% ± 26% (29% to 98%)
Shoulder Extension	**30°sec^{-1}**	100%	51% ± 20% (17% to 95%)	53% ± 22% (24% to 96%)
	120°sec^{-1}	100%	46% ± 22% (11% to 96%)	51% ± 27% (13% to 97%)

Table 1: Group mean ± SD and range (in parenthesis) of strength exerted during feigned and submaximal shoulder flexion and extension efforts expressed as a percentage of maximal efforts.

% Signal Power	Vel.	Maximal Efforts (Hz)	Feigned Efforts (Hz)	Sincere Submaximal Efforts (Hz)	Tolerance Interval Coverage and Level of Confidence	Cut-off Score (Hz)	# of maximal efforts misclassified as non-maximal	# of Non-maximal efforts misclassified as maximal	Sp (%)	Sn (%)
95%	30°/sec	0.68 ± 0.16	7.05 ± 8.92	1.18 ± 0.80	p=0.95 α=0.05 p=0.99 α=0.05	1.03 1.17	2/27 0/27	16/54(4-12) 27/54 (8-19)	92.6 100	70.4 50
	120°/sec	3.91 ± 1.39	11.63 ± 5.23	8.65 ± 4.37	p=0.95 α=0.05 p=0.99 α=0.05	7.04 8.23	0/27 0/27	15/54 (4-11) 24/54 (6-18)	100 100	72.2 55.6
99%	30°/sec	3.27 ± 1.67	18.64 ± 14.45	7.56 ± 4.48	p=0.95 α=0.05 p=0.99 α=0.05	5.77 6.71	3/27 2/27	16/54 (5-11) 23/54 (7-16)	88.9 92.6	70.4 57.4
	120°/sec	16.45 ± 4.72	28.51 ± 7.94	24.37 ± 7.38	p=0.95 α=0.05 p=0.99 α=0.05	27.05 31.08	0/27 0/27	31/54 (9-22) 37/54 (13-24)	100 100	42.6 31.5

Note: **Vel.**, testing velocity; **p**, population percentage estimate; **α**, probability level for a Type 1 error; **Sp**, specificity; **Sn**, sensitivity.

Table 2: Group mean ± SD frequency content scores for maximal, feigned, and self-choice submaximal efforts with accompanying tolerance interval-based cut-off scores for each percentage of signal power and velocity. The performance of the cut-off scores is reported in terms of the number of misclassification per condition and accompanying specificity and sensitivity percentages.

The reasoning for not providing feedback in previous investigations, particularly that of the concurrent visual display of moment-time curves, is due to the possibility of the participants being better able to modulate non-maximal efforts, which has been argued to be not favorable if scores are to be used particularly in medico-legal assessments [28]. However, while there are indications that visual feedback may improve submaximal isometric force target level estimation [29], it is uncertain if this is also the case for dynamic muscular efforts performed at iso-velocity. Thus, this investigation raises the need to systematically assess the effects of various types of feedback, and especially visual feedback on the ability to modulate non-maximal dynamic efforts.

Arguably the more intriguing part from the medico-legal perspective is the ability to differentiate between sincere (either maximal or submaximal) and feigned effort attempts. In the current investigation, it was shown that, on average, feigned effort waveforms exhibit higher frequency content than sincere efforts which are either performed maximally or at a self-selected sub maximal level. However, it was clear that meaningful differentiation between sincere and feigned attempts could not be achieved due to the extremely wide dispersion of feigned effort scores. Thus, the question of how to differentiate effectively between sincere and feigned efforts remains an elusive one. From a theoretical perspective, to the best of our knowledge very little basic research exists that has hypothesized of potential differences in motor control strategies utilized when performing dynamic strength exertions in a sincere manner versus when attempting to deceive. This is an interesting avenue of research, which is likely to combine evidence from several sources to support or refute the proposed hypotheses (e.g. brain imaging, electromyography, strength and psychological measurements). From a practical perspective, however, a less costly endeavor would be to attempt to utilize multivariate approaches for construction of cut-off scores. In the current investigation, we did not attempt to do this due to the likelihood of model over fitting due to a low predictor to observation ratio. However, several investigations pertaining to the topic area of differentiating between maximal and non-maximal efforts have shown that a multivariate statistical model actually improves upon discrimination capabilities [7,8,30,31]. The results of the current investigation suggest that one potential predictor worth considering in the development of such models is the isokinetic moment-time series frequency content. In any case, recall that irrespective of whether non-maximal efforts were performed in a sincere or feigned fashion, both would render test results invalid. The current investigation at least offers some capability in establishing whether strength test results can be used in subsequent decision-making processes of individuals. There are several limitations to our investigation. The first pertains to the clinical applicability of the signal processing method proposed in our paper. To the best of our knowledge, frequency content analysis is not offered in any of the proprietary software offered by isokinetic dynamometer manufacturers. However, frequency content analysis of biomedical signals is a routine topic covered in the education of graduate healthcare and engineering professionals. Given this and the availability of numerous open source software resources, we believe that development of custom in-house analysis programs is feasible and the limitation can be overcome relatively easily through inter-departmental collaborations.

The second limitation of our investigation is that our sample size was relatively small, especially when considering inclusion of the two sexes. Lastly, our sample consisted of healthy participants, and therefore validation of the cut-off scores in those recovering from shoulder injury is warranted.

Conclusion

This investigation is one of less than a handful to analyze isokinetic dynamometer muscular strength output in the frequency domain, and the first to gauge the utility of this measure for purposes of discriminating between maximal and non-maximal concentric, flexion and extension efforts of the shoulder joint. The favorable results attained in our investigation lend support for future studies meant at assessing the utilization of the developed decision rules in those recovering from injuries of the shoulder joint.

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