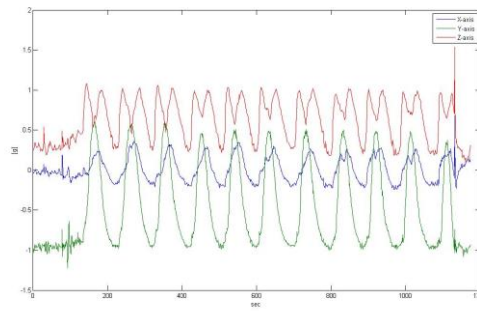


Monitoring neck and shoulder dumbbell exercises using the Sport-sensor



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Background

Musculoskeletal disorders (MSD) are one of the most common and costly issues in public health, especially in the western countries (North America & Europe) [1, 2]. It is a growing problem and one of the major causes of long-term sickness absence [3, 4]. In particular, neck and shoulder related disorders are represented as one of the largest groups of work related MSD's and are frequently represented among workers who engage in highly repetitive upper body working tasks, especially involving static muscle contractions – i.e. computer work [5]. A study carried out on 2576 Danish computer users showed that the 12-month prevalence of more than 7 days of neck pain was around 45%, with women being more prone to developing neck issues than men [6].

Specific strength training targeting the exposed muscle groups are described in the literature as being the most beneficial form of physical exercise training for reducing musculoskeletal pain [7, 8]. Increased strength will result in a smaller sub-maximal loading of the muscles, less accumulation of metabolic substances, improved blood circulation and thereby an enhanced muscle endurance [5, 9].

In order for the prescribed exercises to be effectual, it is essential that they be performed with correct technique in the correct amount of volume and at the right frequency (i.e. training sessions per week). The exercises have been proven to not only rehabilitate but also prevent local muscle pain when careful instruction on exercise performance is given to inexperienced participants [10]. It is likely that people suffering from work related musculoskeletal pain in the neck and shoulder areas are not experienced in performing these types of exercises. Therefore it is of great importance to provide comprehensive instruction on how to perform the exercises correctly. This however, may not be sufficient for repeated correct execution of the exercises, because unaccustomed movements are generally hard to reproduce. It is therefore of interest to be able to provide feedback on the quality of the exercise execution without providing training supervision, as this is very resource demanding and costly. Ideally, movement of all upper body segments should be monitored and evaluated. The best way to do so is with the use of a 3D motion analysis system (i.e. VICON based motion capture). Obviously this method is not feasible for individual unsupervised training, which deems other alternatives necessary.

Another important issue in rehabilitating training is compliance. Several studies have already highlighted the fact that compliance to physical exercise interventions are challenging and report highly different levels of compliance ranging from as low as 35%[11] and up to 85%[12]. Adding motivating factors like gamification or competitive aspects to the training may be a way to improve compliance.

Purpose

The purpose of this study is to investigate if a newly developed sensor (*Sport-sensor*) is applicable for quantifying human upper body movement during various dumbbell exercises and hereby provide sufficient information to be able to present useful feedback regarding the quality and quantity of an exercise execution. The long-term prospect is to develop a user-friendly system, where a single sensor can be mounted in a wristband or a glove and provide feedback on a smartphone or a tablet. Furthermore the idea is to add the “fun” aspect and use the sensor for interaction with games and other apps where the user i.e. can compete with themselves or other people, which might help improve user compliance in the training.

This study validates the Sport-sensor, where four main areas will be investigated.

1. Is the Sport-sensor output valid during different upper body movements when compared to 3D motion analyses (16 camera VICON system), which is considered the ‘gold standard’ of human motion capture?
2. Is the Sport-sensor output reproducible between consecutive repetitions performed by an individual in a given exercise?
3. Is the Sport-sensor output sensitive to discriminate between exercises carried out with different loads?
4. Is the Sport-sensor output specific for different exercises performed?

Research Protocol

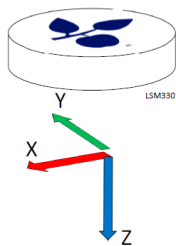
Subjects

Twelve subjects volunteered to participate in the study (6 men and 6 women; age 25 ± 3 years; height 1.70 ± 0.05 m; weight 67.5 ± 11.1 kg). Only two of the subjects (1 man and 1 woman) performed regular dumbbell training for the neck and shoulder muscles.

Sensor

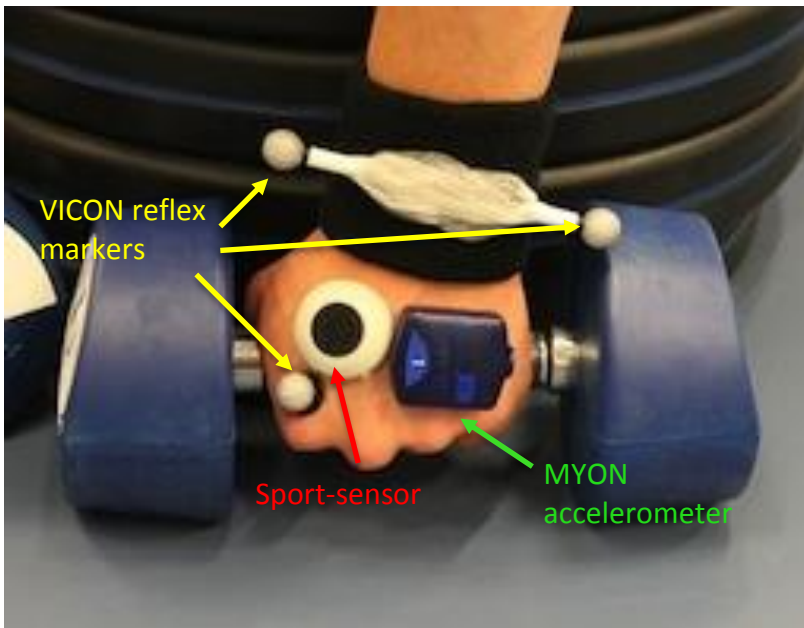
The sensor used in this study is a custom build device containing a three-axial piezo-electrical accelerometer and a rate gyroscope (Fig.1). The accelerometer has a variable sensibility setting with options ranging from 2g to 16g (g = Gravity). The 2g setting was chosen because of the slow movements analyzed in this study, which does not require the ability to sample large magnitudes of acceleration.

Figure 1: Sport-sensor



In the present study only accelerometer data are used, hence all data presented are resultant accelerations of the Sport-sensor, calculated from the accelerations in the three axes. The sensor samples data at a frequency of 20Hz and transfers data via Bluetooth to a tablet containing a supporting application. The electronics has been build into a small cylindrical plastic shell (Fig.2).

Figure 2: Sport-sensor and VICON markers



VICON System

The VICON system (VICON Motion Systems, Oxford, UK) is a marker based 3D motion detection system, which contains 16 infrared cameras (MX-T20s/MX-T40s) (Fig.3). The cameras emit infrared light, which is reflected by circular reflex markers (Fig.4) and captured by the cameras. The cameras are placed around the room so they cover the entire volume used for motion analysis. Data from the 16 cameras are used to triangulate the position and thereby calculate the velocity and acceleration of each marker. Furthermore an accelerometer (MYON 320 accelerometer sensor, MYON AG, Schwarzenberg, Switzerland) synchronized with the VICON system was mounted next to the Sport-sensor in order to register the tap used to synchronize VICON and Sport-sensor data. It was later discovered that the tap was sufficiently distinct from the reflex markers hence the MYON accelerometer data was not necessary and are not presented in this report.

Figure 3: VICON camera (MX-T40s)



Test procedure

The subjects were tested individually in the movement laboratory at the Department of Sports Science and Clinical Biomechanics at the University of Southern Denmark. After a short warm-up period a 1 repetition maximum (1RM) test was performed for each of the five different exercises (Tab.1): This was done to establish the maximal load that could be lifted in each of the exercises with acceptable technique and for calculating 80% and 60% of 1RM, which was later used in the analysis.

Table 1: Exercise description¹

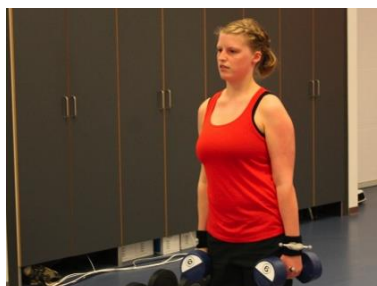
Lateral raise (LAT)

Subject stands in an upright position and lifts her arms to a 90 degree shoulder abduction in the frontal plane



Front raise (FRO)

Subject stands in an upright position and lifts her arm to a 90 degree shoulder flexion



Shrugs (SHR)

Subject stands in an upright position and elevate her shoulders as high as possible



Row (ROW)

Subject is stooped with one arm and leg rested on a training bench and the other arm hanging freely next to the bench. The subject lifts her arm until the dumbbell touches her chest.



Prone Abduction (PRON)

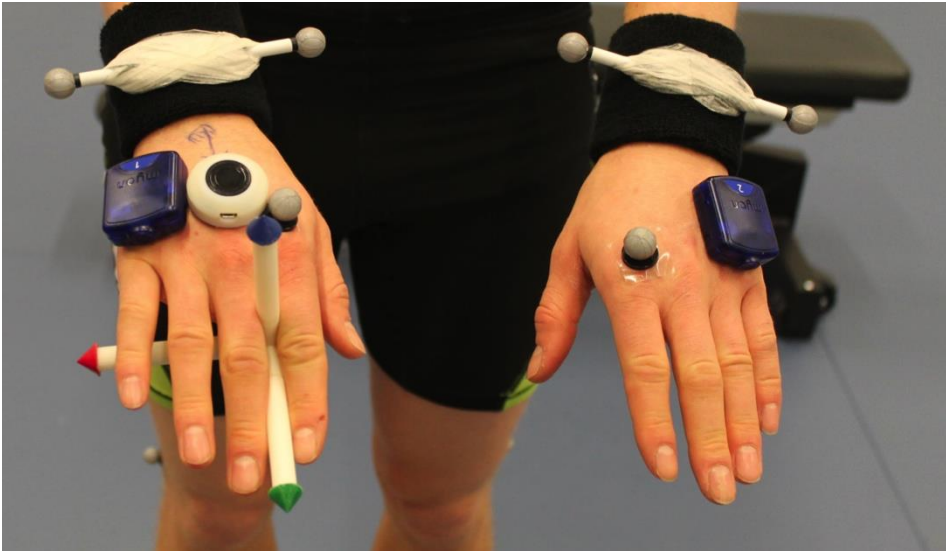
Subject is rested on a training bench facing down with the shoulders free from the bench. The subject performs a 90 degree abduction with simultaneous supination in the wrists, resulting in the thumbs pointing upward.



¹ Introductory videos can be found in the website:
http://www.sdu.dk/Om_SDU/Institutter_centre/job_Idraet_og_biomekanik/Forskning/Forskningsenheder/FysiskAktivitetSundhed/Forskningsprojekter/GameLab4Health

After the 1RM load was established the subject was prepped for testing. The Sport-sensor was mounted on the back of the dominant hand with a marker placed right next to it. Additionally a marker was placed on the opposite hand along with wrist markers (Fig.4).

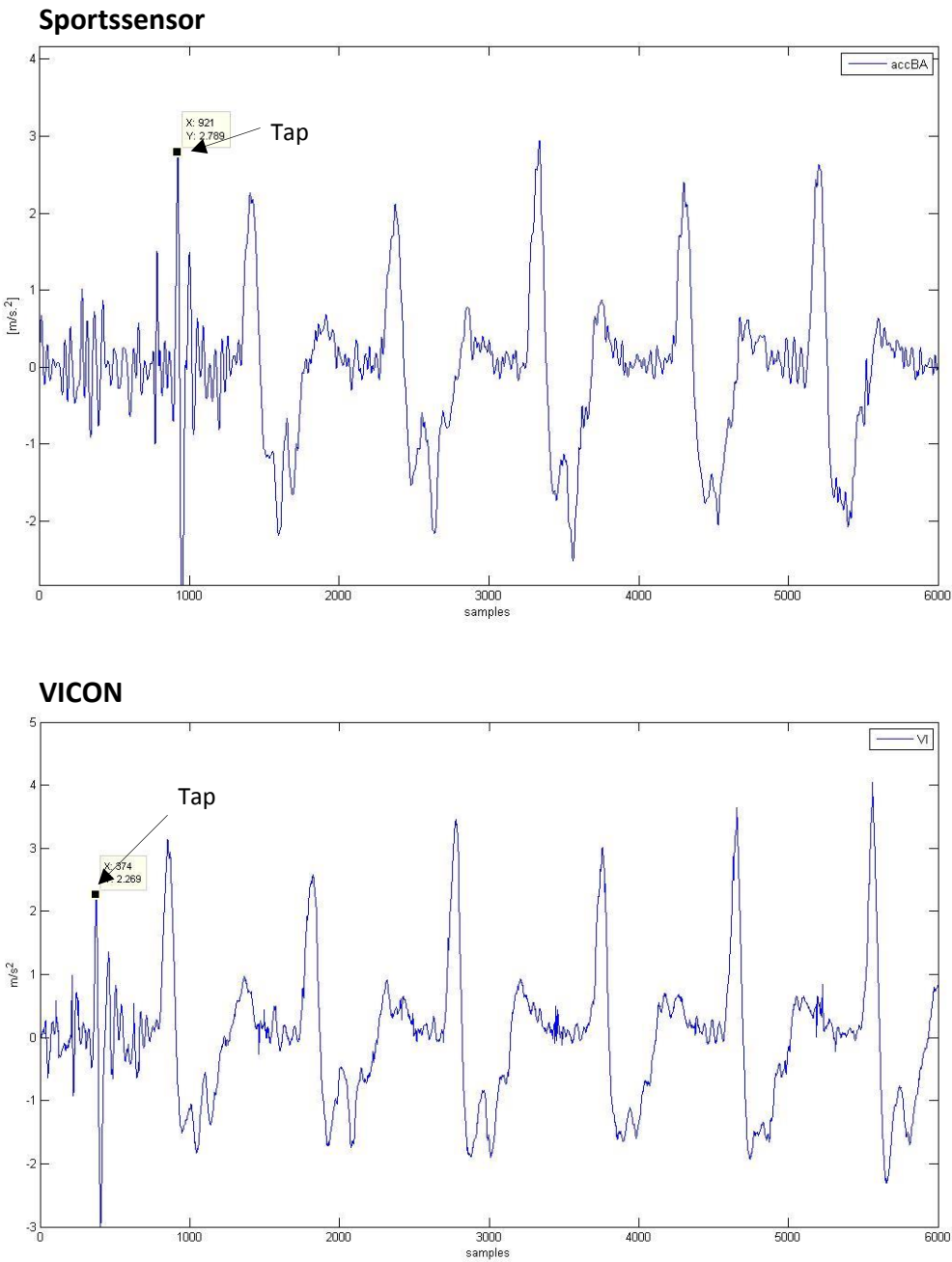
Figure 4: Sensor and marker placement



The five dumbbell exercises were carried out in a randomized order. Each exercise involved performing 80% and 60% of 1RM until exhaustion or until the test leader no longer regarded the technique as acceptable. Within each exercise, the tests were carried out in the mentioned order to minimize the influence of fatigue development. Before the initiation of each test the test-leader gave a light tap on the forearm of the hand on which the Sport-sensor was mounted. This gave a very distinct signal from both markers and the Sport-sensor's accelerometer (Fig.5), which was later used to synchronize data from the two recording systems. Test subjects were instructed to perform the exercises controlled with no rapid movements and not to lift the weight above horizontal line through the shoulders (LAT, FRO, PRON).

During each test session data was sampled from the Sport-sensor at 20Hz and later linear interpolated to 200Hz to fit the VICON signal. At the same time the wrist and hand markers were tracked at 200Hz. Immediately after each test session the test subject was asked to rate their experienced exertion in the affected muscles on an RPE scale (0-10, 0 = nothing at all, 10 = very very hard) [13].

Figure 5: Signal output from a light tap on the forearm

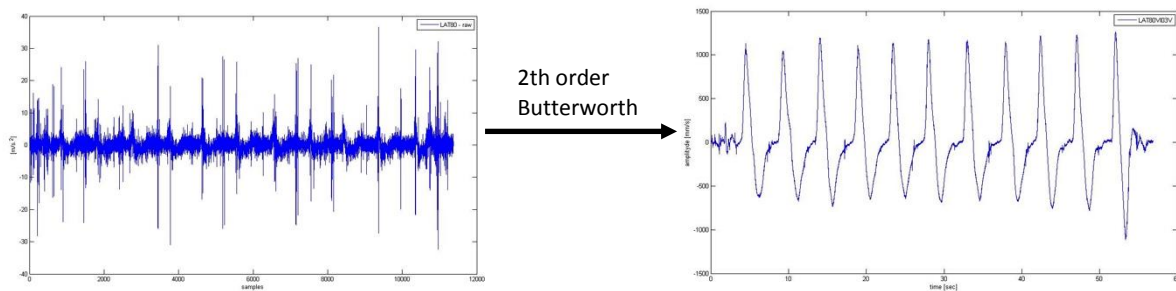


Data analysis

Two subjects were excluded from the data analysis. One subject due to shoulder problems preventing him from completing all the exercises and one subject (the first test subject) due to an unsuitable orientation in the room causing the VICON system to miss a lot of data from the markers resulting in too poor data quality for valid analysis.

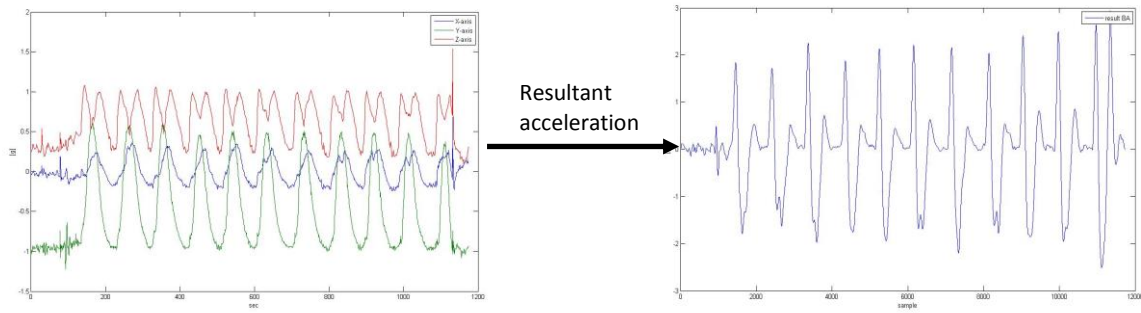
All data obtained from the VICON system was filtered with a 2th order Butterworth filter with a high frequency cut-off at 1-2Hz (LAT 1Hz, FRO 1.5Hz, SHR 1.5Hz, ROW 1.5Hz, PRON 2Hz), removing noise at the highest frequencies (Fig. 6). Data from the Sport-sensor was filtered with the same Butterworth filter, with a cut-off frequency corresponding to the frequency used at the VICON signal.

Figure 6: Butterworth filtering



From the Sport-sensor the accelerations in the three axis (x,y,z) were used to calculate the resultant acceleration of the sensor (Fig.7). The VICON system provides accelerations of the markers in the x, y and z plane in the room in which the experiments was carried out. These were likewise used to calculate the resultant acceleration of the marker placed next to the Sport-sensor. Because the sensor is influenced by gravity the output is not an acceleration of zero when it is held steady, but the output is an acceleration equaling one times gravity ($9.81 \text{ m} \cdot \text{sec}^{-2}$) perpendicular to the center of the Earth. To make the sensor output a signal that is comparable with the VICON signal, which is not affected by gravity, the gravity is simply subtracted from the resultant acceleration measured with the Sport-sensor.

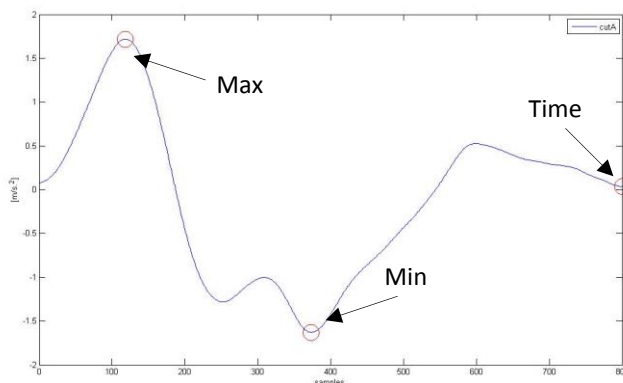
Figure 7: Resultant acceleration of the Sport-sensor calculated from accelerations in the x, y and z-axes



Before analysis was carried out, all data were checked for normality (Shapiro-Wilk test) and homoscedasticity (Barlett's test). Correlation coefficients and Peak-to-peak and time comparison (Fig.8) were used to analyze the validity of the Sport-sensor when compared with the VICON system. Not all data sets presented a Gaussian distribution hence Mann Whitney U test was used to analyze differences in maximum acceleration (Max), minimum acceleration (Min) and duration (Time) between Sportsensor and VICON data, between training loads and between different exercises. Friedman's test was used to analyze differences between consecutive repetitions. Statistical significance was set at $P=0.05$.

All data processing and analysis were carried out in MatLab and all examples presented in the figures are for LAT carried out by the same test subject.

Figure 8: Peak-to-peak and time analysis



Results and discussion

In the following section the four hypotheses will be investigated and discussed in the same order as they are presented in the purpose of this report.

1. Is the Sport-sensor output valid during different upper body movements when compared to 3D motion analyses (16 camera VICON system), which is considered the 'gold standard' of human motion capture?
2. Is the Sport-sensor output reproducible between consecutive repetitions performed by an individual in a given exercise?
3. Is the Sport-sensor output sensitive to discriminate between exercises carried out with different loads?
4. Is the Sport-sensor output specific for different exercises performed?

Validity of the Sport-sensor versus a gold standard

Data from three consecutive repetitions (repetition 2, 3, and 4) from each test subject were used from all the exercises. Data from the three repetitions were pooled to provide higher statistical power.

In all exercises output from the Sport-sensor correlated well with the output from the VICON system with a correlation coefficient of >0.85 except for prone abduction at 60% of 1RM (Tab.2). The correlations indicate that the shape of the acceleration curves from the Sport-sensor is rather similar to the ones from the VICON system. Fig.9 shows a comparison of a filtered signal from the VICON system (1Hz cut-off) and the Sport-sensor (1Hz cut-off). It can be seen from the figure that there are some differences in the two signals especially around zero and at the minimum acceleration. It is possible that the subject lifted the weights a little bit above the horizontal line causing gravity to impact differently on the signal from the Sport-sensor and thereby explaining the differences in the shape of the two curves. Comparison of Max, Min and Time of all exercises revealed that Max and Min for most exercises were significantly different when sampled with the Sport-sensor compared with VICON. Only in one case exercise time was different between the two sampling methods (Tab.3).

Table 2: Correlation - Sport-sensor vs. VICON

	R= \pm SD
LAT60%	0.95 \pm 0.02
LAT80%	0.94 \pm 0.04
FRO 60%	0.92 \pm 0.06
FRO 80%	0.93 \pm 0.05
SHR 60%	0.85 \pm 0.12
SHR 80%	0.85 \pm 0.16
ROW 60%	0.89 \pm 0.13
ROW80%	0.87 \pm 0.15
PRON 60%	0.76 \pm 0.20
PRON 80%	0.86 \pm 0.04

R-values are mean \pm SD of all subjects.

Figure 9: Sensor output VICON (VI) vs. Sport-sensor (BA) from lateral raise at 80%1RM

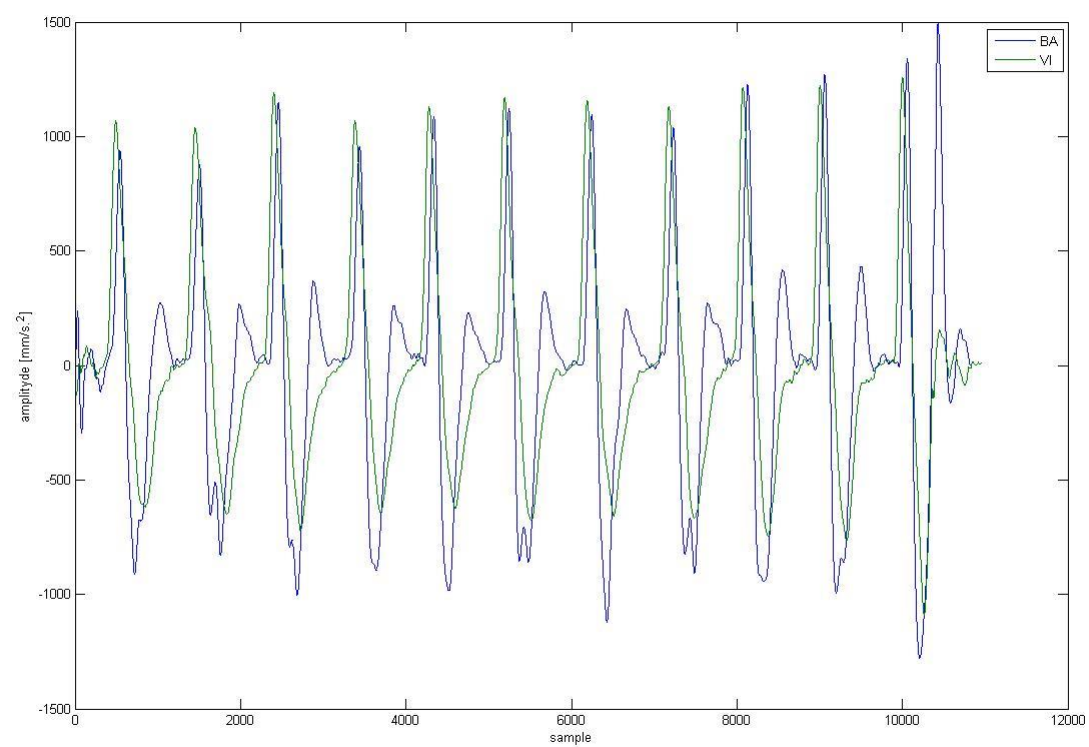


Table 3: Min, Max and Time for Sport-sensor and VICON

	Min ($\text{m}\cdot\text{sec}^{-2}$)		Max ($\text{m}\cdot\text{sec}^{-2}$)		Time (sec)	
	Sport-sensor	VICON	Sport-sensor	VICON	Sport-sensor	VICON
LAT60%	-2.96±0.59	*-2.50±0.61	2.02±0.46	*2.41±0.47	3.21±0.31	3.25±0.36
LAT80%	-2.83±0.70	*-2.41±0.65	1.91±0.51	*2.31±0.48	3.24±0.33	3.33±0.39
FRO 60%	-3.22±0.60	*-2.73±0.51	2.54±0.66	*2.83±0.63	3.08±0.26	3.09±0.28
FRO 80%	-3.05±0.65	*-2.46±0.59	2.40±0.75	2.65±0.68	3.09±0.29	3.18±0.33
SHR 60%	-0.85±0.31	-0.72±0.33	0.81±0.38	*0.63±0.38	2.12±0.44	1.97±0.76
SHR 80%	-0.78±0.31	*-0.61±0.29	0.79±0.49	*0.64±0.47	2.16±0.26	1.96±0.72
ROW 60%	-2.79±0.83	*-2.01±1.04	2.06±0.65	*1.29±0.87	2.49±0.29	2.51±0.35
ROW 80%	-2.61±1.19	*-1.99±1.44	2.02±1.08	*1.31±1.09	2.94±0.56	2.95±0.62
PRON 60%	-3.50±0.89	*-2.83±0.66	2.28±0.88	*3.20±1.18	3.13±0.41	3.18±0.37
PRON 80%	-2.92±0.71	*-2.53±0.56	2.03±0.91	*2.94±1.15	3.14±0.33	*3.34±0.39

* Indicates significantly different from Sportssensor.

Reproducibility of the Sport-sensor output during sampling of consecutive repetitions

In comparison of consecutive repetitions, three repetitions were chosen (No. 2, 3 and 4). There were no differences in Max, Min and Time in the three repetitions in any of the exercises at any training loads. This is expected during the initial repetitions where onset of fatigue is not yet an issue. When fatigue starts to set in it could alter the movement patterns to a degree where the sensor signals are no longer similar. This is however not investigated in this study.

Sensitivity of the Sport-sensor to detect exercise load

In most exercises the load did not influence the execution of the exercise. However in Row there was a significant difference between duration of the repetitions and in prone abduction there was a significant difference in Min acceleration (Tab.4).

Table 4: Influence of training load

	Max ($\text{m}\cdot\text{sec}^{-2}$)		Min ($\text{m}\cdot\text{sec}^{-2}$)		Time (sec)	
	60%1RM	80%1RM	60%1RM	80%1RM	60%1RM	80%1RM
Lateral raise	-2.96±0.59	-2.83±0.70	2.02±0.46	1.91±0.51	3.21±0.31	3.24±0.33
Front raise	-3.22±0.60	-3.05±0.65	2.54±0.66	2.40±0.75	3.08±0.26	3.09±0.29
Shrugs	-0.85±0.31	-0.78±0.31	0.81±0.38	0.79±0.49	2.12±0.44	2.16±0.26
Row	-2.79±0.83	-2.61±1.19	2.06±0.65	2.02±1.08	2.49±0.29	*2.94±0.56
Prone abduction	-3.50±0.89	*-2.92±0.71	2.28±0.88	2.03±0.91	3.13±0.41	3.14±0.33

* Indicates significantly different from 60%1RM.

The lack of systematic differences between loads (i.e. 60%RM vs. 80%RM) could be due to the method of analysis. In this study we just compared maximal acceleration, minimum acceleration and exercise duration. It is likely that the load has greater influence on the initial acceleration at the onset of the movement, and in the turnover phase where acceleration approaches zero, than it has on the Max and Min values. These phases are more difficult to analyze and may also require a higher sample rate in order to reveal differences.

Specificity of the sport sensor to distinguishing between different exercise types

All five exercises were compared pairwise, resulting in ten combinations. Exercises were compared in each of the three parameters - minimum acceleration (Min), maximal acceleration (Max) and duration of the exercise (Time) (Tab.5). In four of the ten combinations there were significant difference between exercises within all three parameters (LAT vs. SHR, FRO vs. SHR, SHR vs. ROW

and SHR vs. PRON), in one combination there was significant difference in two of the three parameters (FRO vs. ROW), in three combinations there were significant difference in one parameter (LAT vs. FRO, LAT vs. ROW and ROW vs. PRON) and in two combinations (LAT vs. PRON and FRO vs. PRON) there were no significant difference between any of the investigated parameters.

Table 5: Comparison of exercises

Max				
	FRO	SHR	ROW	PRON
LAT	0.008	<0.0001	0.243	0.971
FRO		<0.0001	0.019	0.067
SHR			<0.0001	<0.0001
ROW				0.859
Min				
	FRO	SHR	ROW	PRON
LAT	0.240	<0.0001	0.044	0.717
FRO		<0.0001	0.002	0.329
SHR			<0.0001	<0.0001
ROW				0.007
Time				
	FRO	SHR	ROW	PRON
LAT	0.059	<0.0001	0.012	0.252
FRO		<0.0001	0.308	0.554
SHR			<0.0001	<0.0001
ROW				0.176

The presented values in the matrix are p-values of each of the ten combinations in each of the three investigated parameters Min, Max and Time.
Bold values indicate significant difference between exercises.

It is not surprising that the exercise shrugs (SHR) is included in all of the four combinations that revealed significant differences in all three parameters. The movement pattern in shrugs is very different and with a lot smaller range of motion than the rest of the exercises investigated in this study. Neither is it surprising that it is lateral raise (LAT), front raise (FRO) and prone abduction (PRON) that revealed no significant difference in the investigated parameters. The movements are very similar in all three exercises only distinguished by the plane in which the arm is moving. It is possible that gyroscope data is needed to distinguish these three exercises in order to quantify the rotation of the arm and hand and not only the linear displacement.

However the data presented in this study reveals that it is possible to some degree to distinguish exercises on some simple analyzed parameters only by the use of accelerometry.

Conclusions

The purpose of this study was to validate a custom build sensor (Sport-sensor) containing an accelerometer and a gyroscope for the purpose of tracking hand movement during various dumbbell exercises and to investigate whether different training loads and different exercises would impact on the signal output from the sensor.

We found the accelerometer data from the Sport-sensor to correlate well with data sampled from a VICON system during the same exercise execution demonstrating high validity regarding the measure for quality of exercise. However, we found systematic differences in magnitude of the signal output from the sensor and the VICON system regarding maximum and minimum accelerations. Whether these differences are due to different sampling rates of the two systems or due to how the signal from the Sport-sensor was processed remains unknown. The reproducibility of the Sport-sensor output was high when tested during repeated exercises.

Further, it was found that training load could not be discriminated by the Sport-sensor output, which means that accelerometer data alone cannot be used to distinguish different training loads with the analyses performed in this study.

However, there were differences between some exercises (the ones that were most unlike) in the parameters analyzed in this study, which indicates that an accelerometer-based system could be used to distinguish between certain groups of exercises.

Perspective

The above results demonstrate a potential for the Sport-sensor to be used as a feasible feedback tool, when simple dumbbell exercises are performed for the neck and shoulders. However, more sensor data, i.e. gyroscope data might be needed to provide sufficient information on the quality of the exercise execution. As this study is in the initial phase of the development of a feedback system for dumbbell training, we still need to develop a feedback application to be used outside of the laboratory. Furthermore, no study on compliance was conducted in the present study, and future studies should investigate whether or not the Sport-sensor is effective in enhancing compliance, when feedback is provided for the subject. This is vital, as personal training supervision is not always an available resource. Furthermore, unsupervised training or no feedback may have contrary consequences, as incorrect technique can have a deteriorating effect on musculoskeletal pain.

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