Predicting upper limb compensation during prehension tasks in tetraplegic spinal cord injured patients using a single wearable sensor

Conference Paper *in* IEEE International Conference on Rehabilitation Robotics : [proceedings] · June 2019

DOI: 10.1109/ICORR.2019.8779561

9 authors, including:

Sophie Schneider
Uniklinik Balgrist

Werner L Popp
ETH Zurich

Michael Brogioli
University of Zurich

Urs Albisser
Uniklinik Balgrist

2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR)
Toronto, Canada, June 24-28, 2019

Predicting upper limb compensation during prehension tasks in tetraplegic spinal cord injured patients using a single wearable sensor

Sophie Schneider[1], Werner L. Popp[1,2], Michael Brogioli[1], Urs Albisser[1], Stefan Ortmann[1], Inge-Marie Velstra[3], László Demkó[1], Roger Gassert[2], Armin Curt[1]

Abstract— **Upper limb (UL) compensation is a common strategy of patients with a high spinal cord injury (SCI), i.e., tetraplegic patients, to perform activities of daily living (ADLs) despite their sensorimotor deficits. Currently, an objective and sensitive tool to assess UL compensation, which is applicable in the clinical routine and in the daily life of patients, is missing. In this work, we propose a metric to quantify this compensation using a single inertial measurement unit (IMU). The spread of forearm pitch angles of an IMU attached to the wrist of 17 SCI patients and 18 healthy controls performing six prehension tasks of the graded redefined assessment of strength, sensibility and prehension (GRASSP) was extracted. Using the spread of the forearm pitch angles, a classification of UL compensation was possible with very good to excellent accuracies in all six different prehension tasks. Furthermore, the spread of forearm pitch angles correlated moderately to very strongly with qualitative and quantitative GRASSP prehension scores and the task duration. Therefore, we conclude that our proposed method has a high potential to classify compensation accurately and objectively and might be used to quantify the degree of UL compensation in ADLs. Thus, this method could be implemented in clinical trials investigating the effectiveness of interventions targeting UL functions.**

I. INTRODUCTION

Individuals with a spinal cord injury (SCI) often suffer from sensorimotor deficits in the upper limbs (UL) leading to severe limitations in performing activities of daily living (ADLs) and thus decreasing patients' independence. In order to maintain a certain level of independence and to perform ADLs, patients learn compensatory strategies during the rehabilitation process to perform ADLs [1]. A common strategy is the use of a tenodesis grasp, in which SCI patients passively close their fingers by extending the wrist [2]. Furthermore, shoulder abduction is often used to compensate missing elbow extension [1]. Especially the latter can lead to increased shoulder pain and is thus desired to be reduced. Furthermore, compensation is different to biological recovery and thus it is crucial, especially in clinical intervention studies, to distinguish improved function due to compensation from biological recovery [3]. There are clinical assessment tools to measure the upper limb function specific to tetraplegic patients, e.g., the graded redefined assessment of strength, sensibility and prehension (GRASSP) [4] and the Tetraplegia Hand Activity Questionnaire (THAQ) [5]. Although, in the GRASSP assessment the quality of the executed task is rated, this rating is subjective and only binary, i.e., either a patient is showing an altered grip or not. Kinematic analyses using optical marker systems were done to measure UL patterns during ADLs [2], [6]–[8], however this is not applicable in the standard clinical routine. Thus, an easy-to-use tool to objectively classify and quantify UL compensation is missing up to now. Therefore, we propose an objective and unobtrusive tool to assess UL compensation using a single inertial measurement unit (IMU), which is applicable in the standard clinical routine, but also in the daily life of the patients. Furthermore, its potential to not only detect, but also to quantify UL compensation in SCI patients is evaluated, which would allow the application of this proposed method in clinical intervention studies aiming at improving UL function.

[1]Spinal Cord Injury Center, Balgrist University Hospital, Zurich, Switzerland sophie.schneider@balgrist.ch
[2] Rehabilitation Engineering Laboratory, ETH Zurich, Zurich, Switzerland
[3]Clinical Trial Unit, Swiss Paraplegic Center, Nottwil, Switzerland

II. METHODS

A. Subjects

In total, 17 tetraplegic SCI patients and 18 healthy controls were enrolled in this study. Inclusion criteria for the patients were a traumatic or non-traumatic SCI and a neurological level of impairment (NLI) at C7 or above, resulting in impairments in the UL. Patients with all levels of completeness of the lesion (AIS, A: complete and B-D: incomplete) were included in the study. Exclusion criteria were any neurological disease other than SCI, orthopaedic or rheumatic diseases affecting the UL, or an on-going major depression or psychosis. For the healthy controls, the inclusion criterion was an age above 18. Exclusion criteria were any neurological, orthopaedic or rheumatic disease affecting UL function, or an on-going major depression or psychosis.

SCI patients were recruited in the rehabilitation center of the Balgrist University Hospital in Zurich, Switzerland and the Swiss Paraplegic Centre in Nottwil, Switzerland. Healthy controls were recruited from the work environment of the university.

In accordance with the declaration of Helsinki, all subjects signed a written informed consent before participating in the study. This consents also contained the agreement to record videos of the assessments.

The study was approved by the ethical committees of the canton of Zurich (KEK-ZH No. 2013-0202), Lucerne (EK 13018), and the ethical committee of ETH Zurich (EK 2013-N-50).

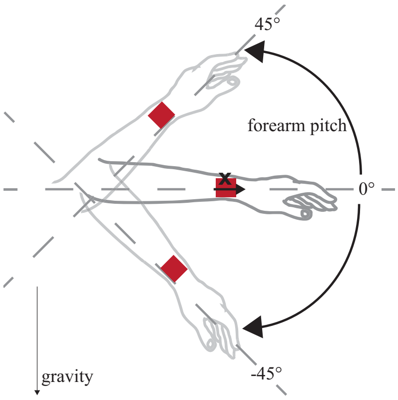

Fig. 1. Schematic representation of the forearm pitch. The pitch angle is calculated relative to the earth referential frame using one inertial measurement unit (red box) attached to the wrist. No pitch, i.e., movement in the horizontal plane, results in a value of 0°. Pointing upwards results in positive values, pointing downwards in negative values.

Fig. 2. Picture of the three investigated qualitative prehension grips. A. Cylindrical grip. B. Lateral grip. C. Pinch grip.

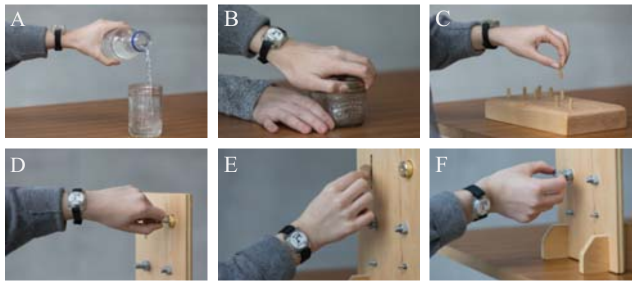

Fig. 3. Picture of all six prehension tasks. A. Pouring water from a bottle. B. Opening a jar. C. Transferring nine pegs from board to board. D. Picking up and turning a key. E. Picking up four coins and placing them into slots. F. Screwing four nuts onto bolts.

B. Measurement protocol

All subjects were told to perform the GRASSP assessment version 1 and were instructed by a therapist or a trained movement scientist. SCI subjects executed each task once, whilst healthy controls performed ten repetitions of all tasks. Note, that not all SCI patients were able to perform all tasks due to their impairments. The execution of the tasks was measured with one IMU attached to each wrist. The x-axis of the sensor always pointed away from the body, i.e., distally (Fig. 1).

1) GRASSP assessment: The GRASSP assessment version 1 is a clinical asssessment tool to assess sensorimotor and prehension function in tetraplegic SCI subjects [9]. It contains three main domains, strength, sensation and prehension. In this study, only the prehension domain was analyzed. The prehension domain consists of two parts, a qualitative and a quantitative assessment. In the qualitative part, three different finger grips (cylindrical, lateral, and pinch grip, Fig. 2) are rated on a scale from 0 to 4. Thereby a score of 0 is equal to no voluntary control of the wrist and hand digits to perform the grip. A score of 4 is equal to a voluntary control of the wrist and hand digits to generate the grip with full force. Scores for all three grips are summed up for a total qualitative GRASSP prehension score.

In the quantitative part, six typical standardized ADLs are performed. The tasks are pouring water from a bottle ('Bottle' Fig. 3A), opening jars ('Jar' Fig. 3B), transferring nine pegs from board to board ('9 pegs' Fig. 3C), picking up and turning a key ('Key', Fig. 3D), picking up four coins and placing them into slots ('Coins', Fig. 3E), and screwing four nuts onto bolts ('Nuts', Fig. 3F). The duration of each task is measured and the quality of the execution is rated on a score from 0 to 5 (quantitative GRASSP prehension score). Scores < 3 are given for no (score 0) or a not completed (score 1 - less than 50%, score 2 - more than 50%) execution of the task, whereas scores ≥ 3 are given for a completed execution with varying quality (score 3 - altered grip, score 4 - appropriate grip with difficulties, score 5 - appropriate grip without difficulties).

2) IMU device: The ReSense sensor was used in this study [10]. The sensor comprises a 3-axis accelerometer (ADXL345, Analog Devices), a 3-axis gyroscope (ITG-3050, InvenSense), a 3-axis magnetometer (MAG3110, Freescale), and a barometric pressure sensor (BMP 085, BOSCH). Data was stored in the internal memory and subsequently transferred to a PC using a custom-made docking station. The desired sampling frequency was set to 50 Hz. Due to varying sampling rates between 49 and 51 Hz, raw data was resampled to 50 Hz by interpolation after transferring to the PC.

C. Data processing

Please note that each hand of each subject was analysed independently, because both hands could have different scores in the GRASSP assessment and in the labeling of UL compensation.

Calculation of forearm pitch: The forearm pitch was calculated relative to the referential earth frame (Fig. 1) by using the acceleration signal and angular velocity rate. The gradient descent algorithm proposed by Madgwick et al. [11] was used to calculate an optimal orientation estimate by fusing the acceleration signal with the angular velocity rate to compensate for the drift resulting from integrating the angular rate. The calculated quaternion presentation was transformed into angles of the pitch relative to the earth referential frame. The approximate error of the calculated pitch angles is 0.6°. For more details about this method see the work of Leuenberger et al. [12]. For visualization purposes, histograms of pitch angles are plotted in polar representation from 90° to -90°with a bin-size of 1°.

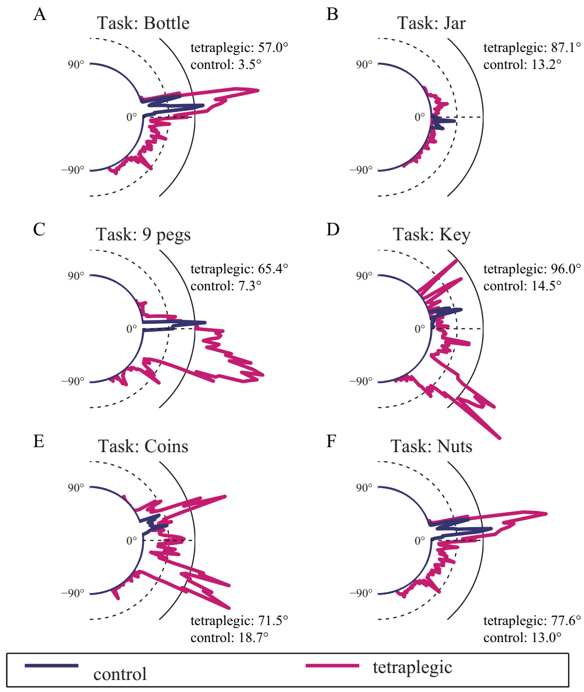

Fig. 4. Polar plots of the forearm pitch angle distribution of a representative SCI patient with compensation (red line) and a control subject (blue line) for each of the six prehension tasks. The outer solid circle denotes a histogram frequency of 100 datapoints (equals to 2sec), the inner dotted line a histogram frequency of 50 datapoints (equals to 1sec). The 95% central range of the forearm pitch is given for one representative tetraplegic and control subject.

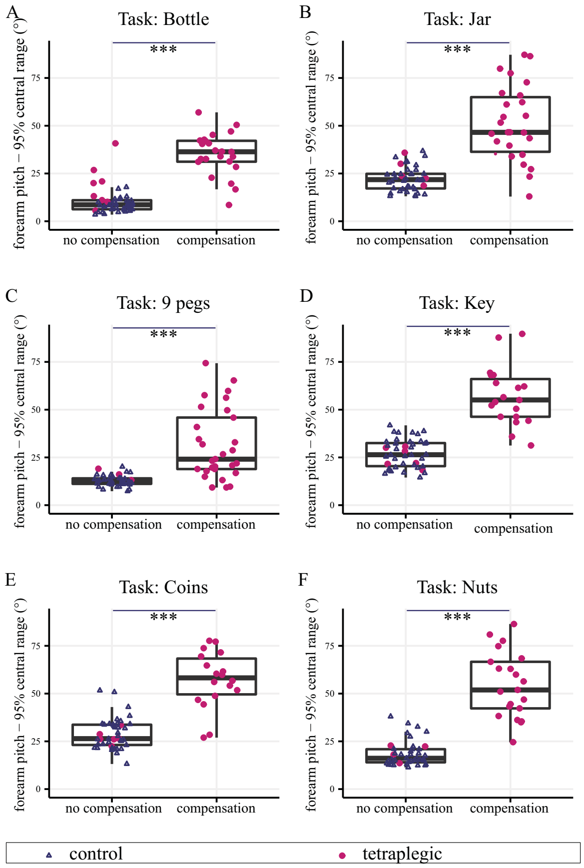

Fig. 5. Boxplots of the spread of the forearm pitch angles in tetraplegic subjects (filled red circles) and healthy controls subjects (empty blue triangles) without compensation and with compensation for all the six prehension tasks.

Manual labeling of compensation: Trained movement scientists were asked to label all video recordings of the GRASSP assessments of both hands and of all subjects separately, while different kinds of compensation were labeled for each task. In this analysis a binarized value of 0 (no compensation) and 1 (any kind of compensation) was used. All further analyses of compensation and no compensation are based on this manual labeling of the tasks.

Measuring task duration: The duration of each of the six prehension tasks was extracted from the labeled video recordings to get more accurate measures compared to the manually assessed time during the GRASSP assessment. For this, each task was labeled in the video recordings by trained movement scientists and its duration was extracted. For the healthy controls, the average task duration of all tasks was taken. For the SCI patients, only task durations of tasks which could be executed completely, i.e., with a quantitative score ≥ 3, were included in the analysis.

D. Statistics

To quantify the spread of the distribution of forearm pitch values, the 95% central range (95% CR) was calculated by:

$$95\%\ \text{CR} = 97.5^{th}\ \text{percentile} - 2.5^{th}\ \text{percentile}$$

Logistic regression was used to predict the compensation (0 - no compensation, 1 - compensation) based on the 95% CR of the forearm pitch as the only predictor. Due to the fact that logistic regression predicts probabilities rather than binary values, a cut-off needs to be specified for the classification problem. The standard cut-off threshold of 0.5 was used, where samples above 0.5 were classified as compensation. 5-fold cross-validation with 10 repetitions was used to validate the predictive model and its sensitivity, specificity, and accuracy calculated to evaluate the predictive power of the model. Within the cross-validation, a resampling technique called random over sampling examples [13] was applied to account for the class imbalance in the present data.

The Spearman correlation coefficient was calculated to assess the strength of the relationship between the spread of forearm pitch angles and the qualitative prehension scores as well as between the spread of forearm pitch angles and the task duration. Firstly, the correlation coefficient was calculated combining all subjects showing and not showing compensation, then, secondly, only for subjects showing compensation.

A Mann-Whitney U test was conducted to evaluate the differences of task duration, qualitative prehension score, and

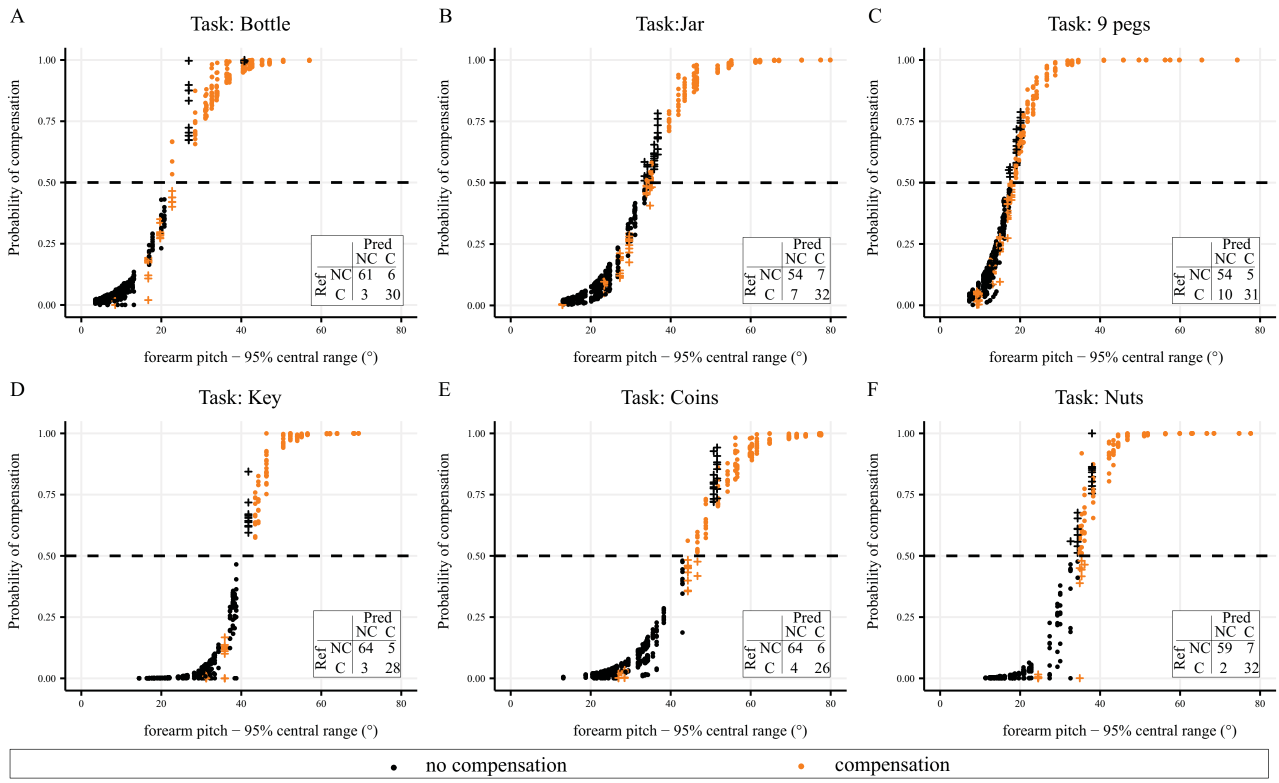

Fig. 6. Predicted probabilities of compensation as functions of the spread of forearm pitch angles using logistic regression. Orange color denotes samples labeled as compensation, black denotes samples labeled as no compensation. Points denote correctly classified samples (true positives and true negatives), crosses incorrectly classified samples (false positive and false negatives). Confusion matrices for all tasks are given in percentages (Pred: predicted score, Ref: labeled score, NC: no compensation, C: compensation).

spread of forearm pitch angles in subjects with and without compensation.

The significance level was set to $\alpha = 0.05$. Correlation coefficients from 0.8 to 1 were defined as 'very strong', from 0.6 to 0.79 as 'strong' and from 0.4 to 0.59 as 'moderate'. [14]. Accuracy values from 0.9 to 1 were defined as 'excellent', from 0.8 to 0.9 as 'very good' and from 0.7 to 0.8 as 'good'. [15]. Statistics was performed in R Studio. Packages *caret* and *ROSE* were used for performing the logistic regression and cross-validation.

III. Results

A. Subject characteristics

The mean age of the included SCI patients was 44.5 $\pm$ 16.8 years, the mean age of the included healthy controls was 36.6 $\pm$ 15.6 years. One of the 17 included SCI patients was female, 5 of the 18 included healthy controls were female. The SCI patients were measured on average 12.5 $\pm$ 9 weeks after their injury. Lesion levels ranged from C3 to C7 (C3: 1, C4: 2, C5: 5, C6: 6, and C7: 3 patients) and AIS scores ranged from A to D (A: 7, B: 4, C: 2, and D: 4 patients).

B. Standard clinical surrogate markers for UL compensation: Qualitative prehension score and task duration

During the bottle task, 23 out of 32 hands showed compensatory strategies, during the jar task 26 out of 31 hands, during the 9 peg task 29 out of 34 hands, during the key 19 out of 25 hands, during the coins 18 out of 24 hands, and during the nuts 21 out of 25 hands. The qualitative GRASSP prehension score in all six prehension tasks was significantly lower in subjects showing compensatory strategies compared to subjects showing no compensatory strategies (Bottle: U = 29, $p < .001$; Jar: U = 6 , $p < .001$; Pegs: U = 7.5, $p < .001$; Key: U = 5, $p < .001$; Coins: U = 5, $p < .001$; Nuts: U = 0.5, $p < .001$). Similarly, the quantitative GRASSP prehension score in all six prehension tasks was significantly lower in subjects showing compensatory strategies compared to subjects showing no compensatory strategies (Bottle: U = 67.5, $p < .001$; Jar: U = 82 , $p < .001$; Pegs: U = 0, $p < .001$; Key: U = 21, $p < .001$; Coins: U = 1, $p < .001$; Nuts: U = 0, $p < .001$). Furthermore, the task duration of all completed tasks (prehension quantity score of ≥ 3) was significantly higher in subjects showing compensatory strategies compared to subjects showing no compensatory strategies in all six prehension tasks (Bottle: U = 854, $p < .001$; Jar: U = 964 , $p < .001$; Pegs: U = 963, $p < .001$; Key: U = 792, $p < .001$; Coins: U = 413 , $p < .001$; Nuts: U = 232, $p < .001$). Median and interquartile range of task durations and qualitative and quantitative GRASSP prehension scores can be found in Tab. I.

TABLE I

TASK DURATION AND QUALITATIVE AND QUANTITATIVE GRASSP PREHENSION SCORES IN SUBJECTS SHOWING COMPENSATORY STRATEGIES AND NOT SHOWING COMPENSATORY STRATEGIES IN THE SINGLE GRASSP TASKS. MEDIAN ± INTERQUARTILE RANGE IS GIVEN.

		compensation	no compensation
Bottle			
	duration (s)	10.8 ± 7.1	5.0 ± 1.1
	qual. prehension score (-)	2 ± 3.5	12 ± 0
	quant. prehension score (-)	3 ± 0	5 ± 0
Jar			
	duration (s)	16.6 ± 19.1	3.2 ± 1.4
	qual. prehension score (-)	2 ± 3.8	12 ± 0
	quant. prehension score (-)	3 ± 0	5 ± 0
9 Pegs			
	duration (s)	26.7 ± 20.4	10.3 ± 1.7
	qual. prehension score (-)	2 ± 4	12 ± 0
	quant. prehension score (-)	3 ± 0	5 ± 0
Key			
	duration (s)	31.1 ± 32.1	3.6 ± 1.1
	qual. prehension score (-)	2 ± 3.5	12 ± 0
	quant. prehension score (-)	3 ± 0	5 ± 0
Coins			
	duration (s)	25.1 ± 25.2	8.2 ± 2.7
	qual. prehension score (-)	2.5 ± 3.8	12 ± 0
	quant. prehension score (-)	3 ± 1	5 ± 0
Nuts			
	duration (s)	55.6 ± 21.6	22.5± 9.1
	qual. prehension score (-)	2 ± 3	12 ± 0
	quant. prehension score (-)	2 ± 2	5 ± 0

C. Sensor-based marker for UL compensation: Spread of forearm pitch angles

Firstly, the spread of forearm pitch angles was significantly higher for subjects showing compensatory strategies compared to subjects showing no compensatory strategies in all six prehension tasks (Bottle: U = 47, $p < .001$; Jar: U = 80, $p < .001$; 9 pegs: U = 145 , $p < .001$; Key: U = 20, $p < .001$; Coins: U = 45, $p < .001$; Nuts: U = 9, $p < .001$; Fig 4 and 5). Secondly, in all six prehension tasks, compensation could be predicted with a very good to excellent accuracy based on the spread of the forearm pitch angles. Sensitivities were very good to excellent, specificities were good to excellent in all six tasks (Tab. II, Fig. 6).

TABLE II

SENSITIVITY, SPECIFICITY, AND ACCURACY OF THE LOGISTIC REGRESSION MODEL FOR CLASSIFYING UL COMPENSATION.

	sensitivity	specificity	accuracy
Bottle	0.9	0.92	0.91
Jar	0.82	0.88	0.86
9 pegs	0.75	0.92	0.85
Key	0.9	0.93	0.92
Coins	0.89	0.92	0.91
Nuts	0.94	0.89	0.91

Furthermore, strong (-0.66) to very strong (-0.83) negative correlations between the qualitative GRASSP prehension score and the spread of forearm pitch angles were found in all six prehension tasks for all subjects (Fig. 7) and strong negative correlations between the quantitative GRASSP prehension score and the spread of the forearm pitch angles

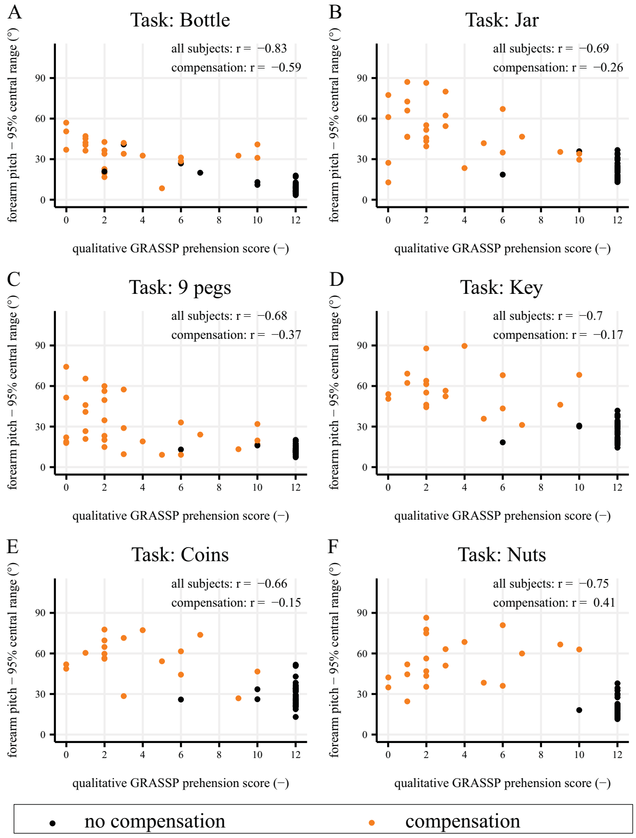

Fig. 7. Correlation between the qualitative GRASSP prehension score (sum of scores for cylindrical, lateral, and pinch grip) and the spread of forearm pitch angles. Orange points denote subjects with labeled UL compensation, black points subjects without labeled UL compensation. Spearman correlation coefficients are shown.

(Fig. 8).

Lastly, the spread of forearm pitch angles showed moderate (0.47) to strong (0.74) positive correlations with the task duration of completed tasks in all six prehension tasks (Fig. 9).

IV. DISCUSSION

In this study, we investigated the potential to use a single wearable sensor to quantify UL compensation in SCI patients for six different ADL tasks. Therefore, we first investigated the applicability of three GRASSP assessment scores to quantify compensation, i.e., the total qualitative and quantitative GRASSP prehension scores and the task duration during the quantitative testing of the GRASSP to find surrogate markers of UL compensation. These surrogate markers could then serve as a validation score for the sensor-based metric we propose. We hypothesized that subjects with lower values of qualitative and quantitative GRASSP prehension scores were more likely to show compensatory strategies to handle ADLs. Additionally, it can be assumed that the usage of compensatory strategies would result in a longer movement duration as shown in [6], and thus act as a surrogate marker for compensation.

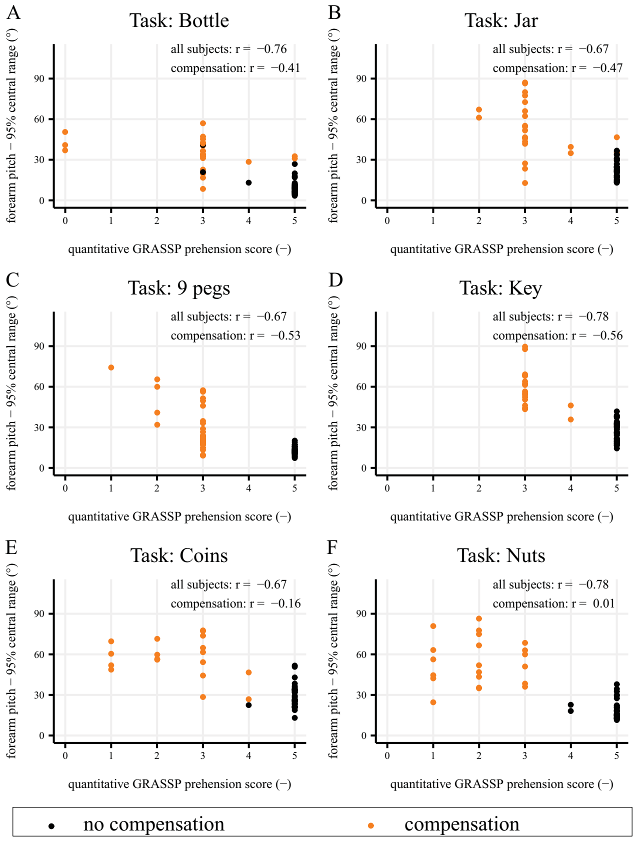

Fig. 8. Correlation between the quantitative GRASSP prehension score and the spread of forearm pitch angles for each task. Orange points denote subjects with labeled UL compensation, black points subjects without labeled UL compensation. Spearman correlation coefficients are shown.

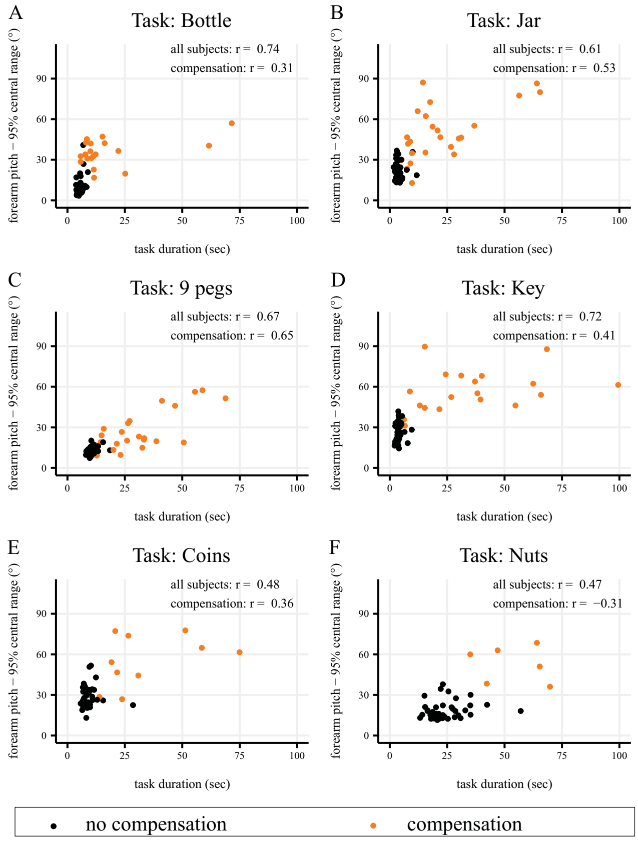

Fig. 9. Correlation between the task duration and the spread of forearm pitch angles for each task. Orange points denote subjects with UL compensation, black points subjects without UL compensation. Spearman correlation coefficients are shown.

Subjects with UL compensation showed decreased values of qualitative and quantitative GRASSP prehension scores compared to subjects without compensation, confirming our hypothesis. Furthermore, UL compensation was found to result in an increased movement duration. Subjects showing compensatory strategies had longer task durations in all six investigated prehension tasks. Therefore, our hypothesis that task duration can be interpreted as a surrogate marker for compensation was confirmed and thus, could be used as an additional marker to validate the proposed sensor-based metric.

The extracted spread of forearm elevation angles was found to be higher in subjects showing compensation than in subjects showing no compensation, suggesting a relationship between the spread of angles and the usage of compensatory strategies. Based on the spread of forearm pitch angles, we were able to classify UL compensation and no compensation with very good to excellent accuracies. This confirms the potential to use the spread of forearm elevation angles extracted from a single wearable sensor to detect compensatory strategies in subjects with an UL impairment. We hypothesize that our tool mainly detects compensatory strategies in which a shoulder abduction is involved. Thus, it performs less good in tasks like the 9 pegs task, in which compensation can only be done by altering the grip (e.g. using a lateral grip instead of a pinching grip), which does not involve compensation by a shoulder abduction. However, an increased contribution of the shoulder during reaching and pointing tasks has been shown previously [7], [16]. Therefore, we hypothesize that our proposed metric is able to detect most of the UL compensatory strategies that occur in SCI patients.

Lastly, we investigated the relation between the spread of forearm pitch angles and the qualitative and quantitative GRASSP prehension scores as well as the task duration as a surrogate marker for compensation. We found moderate to very strong correlations in all six tasks, which might confirm the potential of the spread of forearm elevation not only as a binary classifier but also as an objective and sensitive metric to quantify the magnitude of compensation. However, correlations were less strong in some tasks, e.g., coins, when analyzing correlations within the group of subjects showing compensation. This suggests that not all tasks might be suited equally well to quantify the degree of compensation.

Nonetheless, a true ground truth for the magnitude of compensation is missing. Therefore, more research needs to be invested to confirm the potential of this metric to sensitively quantify the magnitude of compensation, e.g.

by acquiring ground truth data by using a motion tracking system. Furthermore, the six standardized ADLs were investigated within a clinical environment. Although these tasks are representative, they do not cover the complete spectrum of prehension tasks occuring during daily life. The execution of ADLs during daily life may also be altered due to external circumstances like the usage of assistive devices and may thus show altered patterns.

V. CONCLUSIONS

We presented an objective and accurate metric to assess UL compensation in tetraplegic SCI patients using wearable sensors. This metric can be applied in clinical intervention studies to examine the presence of UL compensation as an outcome measure in an unobtrusive way and help to understand the true recovery of UL functions in SCI patients. Moreover, the reduction and thus detection, especially of shoulder compensation, is of high interest to prevent and minimize shoulder pain, which has a huge impact in terms of independence as well as of quality of life in SCI patients [17]. Furthermore, we showed the potential of applying this tool not only as a binary classifier, but also as a sensitive marker to quantify the magnitude of compensation. However, this potential still needs to be validated in further studies. Compared to standard clinical assessments for UL function like the GRASSP, our metric can be applied during the daily life of patients and thus give insights into the performance of ADLs outside of the clinical environment. It could complement existing frameworks focusing on the quantity of physical activity [18]–[21] by a qualitative component. However, more research needs to be invested to be able to detect ADLs in daily life. We believe that our metric for detecting compensatory movements in the ULs is not limited to the population of SCI, but could also be applied in other populations with neurological conditions, i.e., stroke.

ACKNOWLEDGMENT

We would like to thank Larissa Angst, Karin Akermann, and Anne Brust for their help in recruiting subjects and performing the assessments and Anika Ballmer for her help in the manual labeling of the compensation. This study has been funded by the International Foundation for Research in Paraplegia (IRP, project number: P 157), by the Clinical Research Priority Program (CRPP) Neuro-Rehab of the University of Zurich, by Wings for Life (project number: 143), by the Swiss Paraplegic Foundation (SPS), by the ETH Zurich Foundation in collaboration with Hocoma AG, by a HMZ seed project (project title: ZurichMOVE: Wearable sensors to monitor movement quality and mobility in health care) funded by the University of Zurich and the ETH Zurich Foundation, and by the Swiss State Secretariat for Education, Research and Innovation (SERI) under contract number 15.0255 (Horizon 2020, 681094).

REFERENCES

[1] S. Mateo, A. Roby-Brami, K. T. Reilly *et al.*, "Upper limb kinematics after cervical spinal cord injury: A review," *Journal of NeuroEngineering and Rehabilitation*, vol. 12, no. 1, p. 9, 1 2015.

[2] S. Mateo, P. Revol, M. Fourtassi *et al.*, "Kinematic characteristics of tenodesis grasp in C6 quadriplegia," *Spinal Cord*, vol. 51, no. 2, pp. 144–149, 2 2013.

[3] A. Curt, H. J. A. Van Hedel, D. Klaus, and V. Dietz, "Recovery from a spinal cord injury: significance of compensation, neural plasticity, and repair." *Journal of Neurotrauma*, vol. 25, no. 6, pp. 677–685, 2008.

[4] S. Kalsi-Ryan, D. Beaton, A. Curt *et al.*, "The Graded Redefined Assessment of Strength Sensibility and Prehension: Reliability and Validity," *Journal of Neurotrauma*, vol. 29, no. 5, pp. 905–914, 3 2012.

[5] N. E. Land, E. Odding, H. J. Duivenvoorden *et al.*, "Tetraplegia Hand Activity Questionnaire (THAQ): The development, assessment of arm-hand function-related activities in tetraplegic patients with a spinal cord injury," *Spinal Cord*, vol. 42, no. 5, pp. 294–301, 5 2004.

[6] A. De Los Reyes-Guzmán, A. Gil-Agudo, B. Peñasco-Martín *et al.*, "Kinematic analysis of the daily activity of drinking from a glass in a population with cervical spinal cord injury," *Journal of NeuroEngineering and Rehabilitation*, vol. 7, no. 1, 2010.

[7] I. Laffont, E. Briand, O. Dizien *et al.*, "Kinematics of prehension and pointing movements in C6 quadriplegic patients," *Spinal Cord*, vol. 38, no. 6, pp. 354–362, 6 2000.

[8] E. W. A. Cacho, R. De Oliveira, R. L. Ortolan *et al.*, "Upper limb assessment in tetraplegia: Clinical, functional and kinematic correlations," *International Journal of Rehabilitation Research*, vol. 34, no. 1, pp. 65–72, 3 2011.

[9] I.-M. Velstra, A. Curt, A. Frotzler *et al.*, "Changes in Strength, Sensation, and Prehension in Acute Cervical Spinal Cord Injury: European Multicenter Responsiveness Study of the GRASSP." *Neurorehabilitation and neural repair*, vol. 29, no. 8, pp. 755–766, 2015.

[10] K. Leuenberger and R. Gassert, "Low-power sensor module for long-term activity monitoring." *Conf Proc IEEE Eng Med Biol Soc*, vol. 2011, pp. 2237–2241, 2011.

[11] S. O. H. Madgwick, A. J. L. Harrison, and R. Vaidyanathan, "Estimation of IMU and MARG orientation using a gradient descent algorithm," *IEEE International Conference on Rehabilitation Robotics*, 2011.

[12] K. Leuenberger, R. Gonzenbach, S. Wachter *et al.*, "A method to qualitatively assess arm use in stroke survivors in the home environment," *Medical and Biological Engineering and Computing*, vol. 55, no. 1, pp. 141–150, 2017.

[13] G. Menardi and N. Torelli, "Training and assessing classification rules with imbalanced data," *Data Mining and Knowledge Discovery*, vol. 28, no. 1, pp. 92–122, 1 2014.

[14] J. D. Evans, *Straightforward Statistics for the Behavioral Sciences.* Brooks/Cole Pub. Co, 1996.

[15] A.-M. Šimundić, "Measures of Diagnostic Accuracy: Basic Definitions." *EJIFCC*, vol. 19, no. 4, pp. 203–11, 1 2009.

[16] J. Jacquier-Bret, N. Rezzoug, J. M. Vallier *et al.*, "Reach to grasp kinematics and EMG analysis of C6 quadriplegic subjects," in *Proceedings of the 31st Annual International Conference of the IEEE Engineering in Medicine and Biology Society: Engineering the Future of Biomedicine, EMBC 2009*. IEEE, 9 2009, pp. 5934–5937.

[17] S. K. Salisbury, N. L. Choy, and J. Nitz, "Shoulder pain, range of motion, and functional motor skills after acute tetraplegia," *Archives of Physical Medicine and Rehabilitation*, vol. 84, no. 10, pp. 1480–1485, 10 2003.

[18] D. Zbogar, J. J. Eng, W. C. Miller *et al.*, "Reliability and validity of daily physical activity measures during inpatient spinal cord injury rehabilitation," *SAGE Open Medicine*, vol. 4, p. 2050312116666941, 2016.

[19] M. Brogioli, S. Schneider, W. L. Popp *et al.*, "Monitoring Upper Limb Recovery after Cervical Spinal Cord Injury: Insights beyond Assessment Scores." *Frontiers in Neurology*, vol. 7, p. 142, 2016.

[20] M. V. Albert, Y. Azeze, M. Courtois, and A. Jayaraman, "In-lab versus at-home activity recognition in ambulatory subjects with incomplete spinal cord injury," *Journal of NeuroEngineering and Rehabilitation*, 2017.

[21] W. L. Popp, L. Richner, M. Brogioli *et al.*, "Estimation of energy expenditure in wheelchair-bound spinal cord injured individuals using inertial measurement units," *Frontiers in Neurology*, vol. 9, p. 478, 2018.