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Technical note

Design and validation of the Grip-ball for measurement of hand grip strength

Rana Jaber*, David J. Hewson, Jacques Duchêne

Institut Charles Delaunay, UMR CNRS 6279, Université de Technologie de Troyes, 12 rue Marie Curie, BP2060, 10010 Troyes, France

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ABSTRACT

The Grip-ball is a new dynamometer used to evaluate grip strength, as well as for use in home-based rehabilitation of the hand and forearm. The Grip-ball consists of pressure and temperature sensors and an electronic wireless communication system contained in an airtight ball. That can be inflated to different pressures. The device has advantages over standard dynamometers in that it looks like a simple ball, and can wirelessly communicate via Bluetooth to any compatible receiver, thus have potential to be used for clinical assessment and rehabilitation in a remote setting. The reliability and reproducibility of the device were assessed for the pressure sensor itself, as well as the relationship between the force applied and the pressure measured by the Grip-ball. The initial validation was performed using the pressure sensor without the ball in order to confirm the accuracy of the sensor used. A second validation study was conducted using the Grip-ball rather than just its sensor to examine the relationship between the pressure measured inside the ball and force applied. The results showed that there is a very good correlation ($r = 0.997$, $p < 0.05$) between the pressure measured by the Grip-ball sensor and that measured by a Vigorimeter, thus confirming the reliability of the sensor used in the Grip-ball. A quadratic regression equation was calculated in order to predict the force applied based on the pressure measured inside the ball, and the initial pressure to which the ball was inflated ($R^2 = 0.97$, standard error 10.9 N). Such a finding compares favourably with the variability inherent in Jamar recordings, thus indicating that the Grip-ball could be used to assess grip force. An industrial version of the Grip-ball, which is currently under development, will be able to be used for the entire range of grip force in the population.

1. Introduction

Grip strength measurement provides valuable information that can be used to quantify the functional status of the upper limb [1,2] or even the entire neuromuscular system [3]. Grip strength can also be used as a measurement of the degree of impairment in respect to neuromuscular or neurological disabilities suffered after trauma or surgery. In addition, grip strength is a good indicator of the overall physical state of an individual, in respect to their capacity to live autonomously. Such information is of particular interest in an elderly population with respect to their physical frailty [4]. Grip-strength measurement has also been shown to be correlated with clinical tests, such as the Index of Activities of Daily Living (IADL) [5], and with tests such as the Timed up-and-go (TUG) [6].

Evaluation of grip strength offers numerous advantages in comparison to other tests. Grip-strength evaluation is simple, easy to perform, and is also highly reproducible [7]. Given these advantages, grip-strength is often used as an aid in characterising the degree of impairment, for instance in the evaluation of the damage suffered due to an accident, or as an aid in characterising the degree of improvement, for instance in the evaluation of the therapeutic effects of a treatment. In addition, grip strength has a major advantage in respect to clinical tests such as the IADL and the TUG in that it is completely objective, and could potentially be self-administered [7]. The fact that grip strength can be measured without requiring the presence of a health professional enables grip strength to be measured remotely, provided a suitable recording device with inbuilt communication functionality is used.

Standard re-education practices after trauma or hand surgery often require treatment to begin as early as possible in order to obtain an optimal physical improvement. Such rehabilitation sessions typically require at least 30 min, according to the general classification system of medical treatments used in France. In addition to the rehabilitation itself, patients are also required to travel to the healthcare professional, thus greatly increasing the time required and the difficulty inherent in following the rehabilitation programme.

The main devices currently used to evaluate grip strength [Jamar (Sammons & Preston, Bolingbrook, IL, USA), Martin Vigorimeter (Martin Medizintechnik, Tuttlingen, Germany), Lode (Lode dynamometer; Lode BV, Groningen, The Netherlands), and the MIE digital pinch/grip (MIE Medical Research Ltd, Leeds, United Kingdom)] or for re-education of the hand [(Handmaster Plus

* Corresponding author. Tel.: +33 3 25 71 84 50.
E-mail addresses: rana.jaber@utt.fr (R. Jaber), david.hewson@utt.fr (D.J. Hewson), jacques.duchene@utt.fr (J. Duchêne).

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(CefarCompex, Mouguerre, France), Grippers (IronMind Enterprises, Inc., Nevada City, CA, USA)] are almost exclusively reserved for healthcare professionals, rather than for use in a non-controlled home-based assessment and they do not allow regular assessment followed by a healthcare professional.

Given the inconveniences of current dynamometers and the advantages of an automatic grip-strength measurement system, it was decided to design a device that could be used in home-based grip-strength assessment and rehabilitation of the hand and forearm. The Grip-ball was conceived to overcome the restrictions observed for the other devices, and also to propose an easy-to-use device that could also be used remotely by means of an automatic communication system.

2. The Grip-ball

The Grip-ball [8] consists of an airtight, supple, inflatable plastic ball containing pressure and temperature sensors, a digitisation function, and a communication system (Fig. 1). Communication is performed via Bluetooth, thus ensuring interoperability with other local devices that could store or transfer the data (computer, tablet, mobile phone, etc.). The Grip-ball transmits the pressure measured by the sensor inside the ball in real time, when the ball is squeezed. The pressure applied is proportional to the force exerted by the user.

2.1. Design

A plastic ball (Spordas All-Balls™, Idemasport, Villeneuve d'Ascq, France) was used as the envelope of the system. The ball contains a valve that enables the initial internal pressure to be modified via inflation. The surface of the ball is smooth and supple, meaning that it would be comfortable for the users to squeeze.

The electronic circuit, which measures 45 mm in diameter, and 30 mm in height (Fig. 1), is fixed to the internal part of the valve (in the industrial version, it is expected to move freely inside the ball). It is equipped with a pressure sensor (MS5535C, RoHS, Intersema Sensorielle SA, Bevaix Switzerland), which has a measurement range of 0–1400 kPa and a 15-bit analogue-to-digital conversion. The sensor is managed by a controller (PIC 18LF13K22 Microchip transmitter Bluetooth ARF32 Adeumis, Crolles, France), which acquires the sensor data, and transmits them via Bluetooth to a receiver.

2.2. Power supply

Two prototype devices were developed, each with a different power supply design. The first makes use of standard batteries (Li-SOCI2 technology, capacity 1100 mAh, Saft, Bagnolet, France), allowing a continuous transmission for a 36-h period. Obviously, such a system is not practical, as the electronic components required to measure and transmit the pressure signal must be sealed inside the ball. To this end, a reed switch was used to disconnect the battery from the electronic circuits when the ball was not in use. The switch can be turned off by placing the ball in a support base containing a magnet, which turns the reed switch off.

The second prototype version includes a rechargeable system to increase the autonomy of the device without requiring the ball to be opened up and the battery changed. Accordingly, a rechargeable NiMH battery was used, with battery selection based on cost, safety, and life cycle criteria. The chosen battery is able to accept high currents, and also has no memory effect. The recharging of these batteries is performed using wireless inductive coupling between the base (including the primary coil and the associated electronics) and the ball where the secondary coil is inserted, along with the battery load electronics.

The secondary charge circuit is mounted on another PCB that is attached to the valve of the ball.

The electronics of the Grip-ball is disconnected and the battery begins to recharge automatically as soon as the ball is placed into the base (Fig. 1d), Removal of the ball from the base stops the recharging process and activates the internal electronics, hence allowing the ball to be used again. If the ball is not used for 10 min, the device switches to the low-power mode in order to increase autonomy. Placing the ball back into the base for two seconds, and then removing it, automatically reactivates the measuring system.

2.3. Insertion of the electronic circuits in the ball

In the prototype version of the Grip-ball, the electronic measurement system is inserted into the ball through a slit that is made in the ball. The measuring system is attached to the valve of the ball using through a homemade stand, after the ball has been turned inside out. The electronic circuit and the stand are then coated in a rubber sheath in order to ensure the system is airtight, before the ball is turned back the right way round, with the electronics on the inside of the ball. The final step in the process is to hermetically seal the ball. This process was designed only for the "proof of concept" version of the Grip-ball, and will be replaced by an industrial process in which the ball will be built around the electronic components.

3. Testing methodology

Validation tests were conducted in two steps, the first of which was a comparison between the pressure measured by the sensor in the Grip-ball and that given by a reference device, the Martin Vigorimeter. The second validation consisted of a series of measurements in which an external force applied to the Grip-ball by a specialised device was compared to the pressure measured by the Grip-ball.

3.1. Validation of the Grip-ball sensor

The Martin Vigorimeter is a dynamometer used to measure grip strength, and is the closest such device to the Grip-ball, in that it measures pressure rather than force. The device consists of a bulb that is attached via a tube to a manometer. The device has a two-needle display to indicate the instantaneous pressure (in black) and the maximal pressure (in red), since the last zeroing of the device. The manometer has scales in kilopascals and bar, with a maximum value of 160 kPa (1.6 bar) and a resolution of 2 kPa (0.02 bar). The Vigorimeter records pressure relative to atmospheric pressure, meaning the scale starts at zero. Three different sizes of bulb are available, depending on the circumference of the hand of the person being tested.

In order to compare readings from the Martin Vigorimeter with those obtained from the Grip-ball sensor, the Vigorimeter was modified. The Grip-ball sensor, complete with electronic circuit and the wireless communication facilities, was added into the tube between the bulb and the manometer (Fig. 2a and b). The force applied was standardised by using a Motorized test stand Stentor (Stentor 2, ANDILOG, Vitrolles, France). The Stentor is a comprehensive measurement system that applies a calibrated force at a controlled velocity onto any surface placed under a mobile arm (Fig. 3). The modified Vigorimeter was placed between the mobile arm and the base of the Stentor. The surface of the Stentor in contact with the device tested can be changed, depending on the requirements of the testing protocol being followed. In the first test, where force was applied to the bulb of the Vigorimeter, a hemisphere surface measuring 20 cm^2 was used (Fig. 3). The mobile arm of the Stentor is equipped with a strain gauge, which measures the

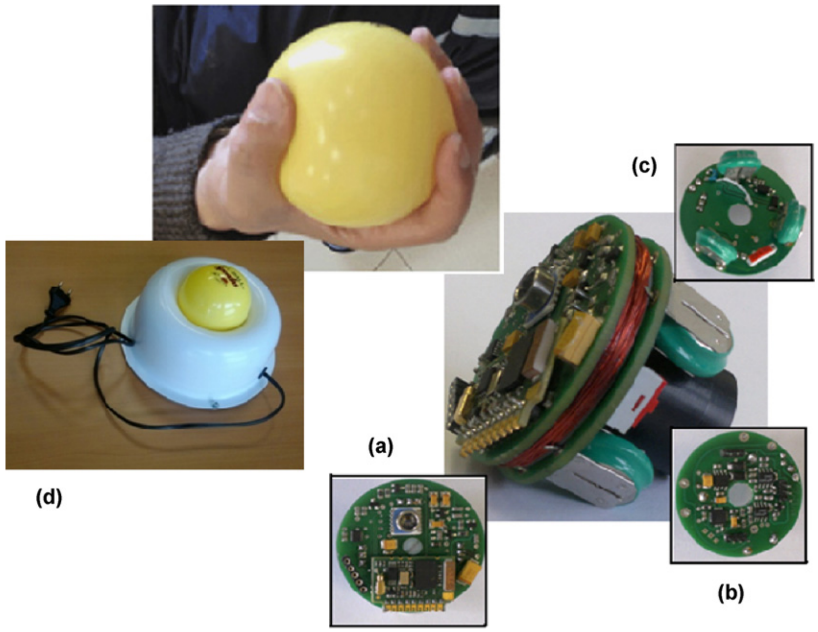

Fig. 1. The Grip-ball and its internal electronics: (a) sensor and communication modules; (b) sensor side; (c) battery side; (d) the Grip-ball in its recharging base.

instantaneous force applied. This force value is displayed on a digital display and can also be transmitted to a computer via a standard RS232 connection.

A range of forces was applied to the largest Vigorimeter bulb in order to cover the whole pressure range of the manometer. The pressure value displayed on the Vigorimeter manometer was noted manually. The values measured by the Grip-ball sensor, which were sampled at 15 Hz, were sent to a computer via the Bluetooth connection included in the electronic circuit. The final pressure value recorded from the Grip-ball sensor was taken as the sensor value of

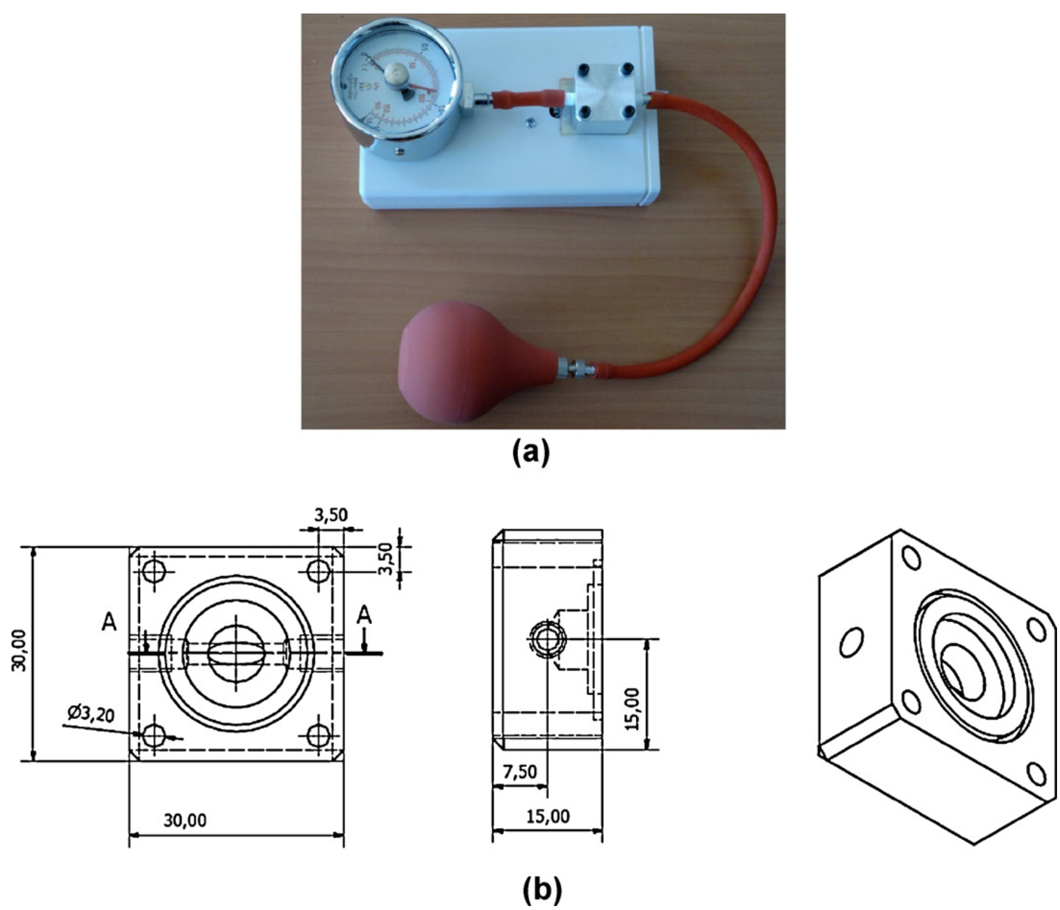

Fig. 2. The Vigorimeter combined with the Grip-ball electronics. (a) Device overview. (b) Mechanical deviation chamber.

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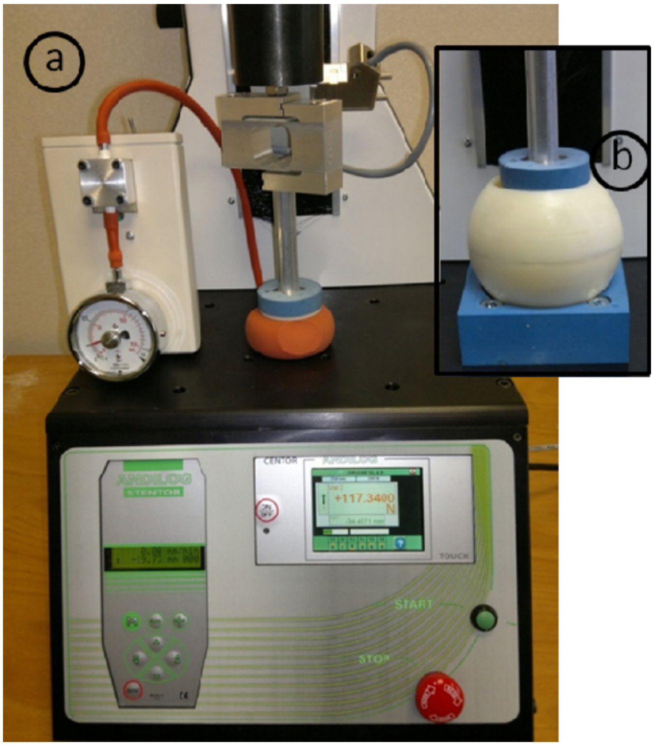

Fig. 3. Stentor force calibration system applying a calibrated force onto: (a) the modified Vigorimeter; (b) the Grip-ball contained within the rigid sphere.

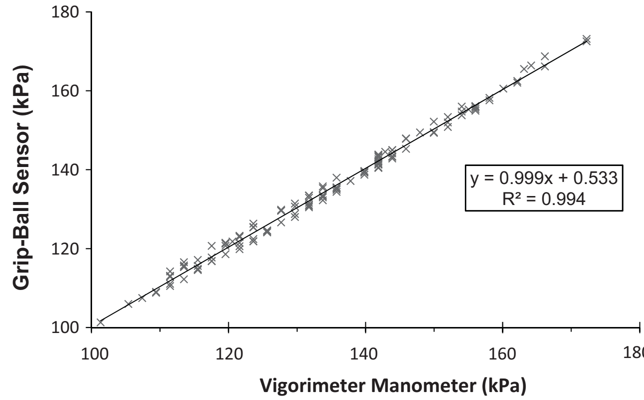

Fig. 4. Relationship between the Grip-ball pressure sensor and the Martin Vigorimeter. The linear regression equation and the coefficient of determination are shown.

the recorded signal, with measurements expressed in kPa. The Grip-ball pressure value was compared with the value obtained from the manometer. All pressure values were adjusted to atmospheric pressure, which was taken to be 101.326 kPa. Linear regression was performed in order to compare the pressure values obtained from the two systems. All statistical tests were performed using the Statistical Package for Social Sciences (IBM-SPSS Version 20, IBM Inc., Armonk, Town of North Castle, NY, USA).

3.2. Relationship between the external force applied and the Grip-ball pressure

The Grip-ball is an airtight system, for which the internal pressure can be modified, as for any inflatable ball equipped with a valve. In contrast to the Martin Vigorimeter, for which the bulb is always at atmospheric pressure, the Grip-ball can be used to evaluate grip strength with different initial pressures. Such differences in initial pressure would lead to changes in stiffness and the corresponding dynamics of grip strength measurement or rehabilitation exercises. It was necessary, therefore, to establish reference curves between the applied force and the internal ball pressure, for a range of different initial pressures.

The Stentor, described in Section 3.1 above was also used to help determine the relationship between force and pressure. In this experiment force values were continuously measured via an RS232 connection, and sampled at 100 Hz.

For this second validation study, the Grip-ball was placed inside a rigid sphere of 90 mm diameter, which consisted of two hemispheres screwed together (Fig. 3). The upper hemisphere had a disc shaped piece measuring 55 mm diameter removed from the top and attached to the mobile arm of the Stentor. This disc shaped piece served as the contact element of the mobile arm of the Stentor. The spherical container was used in an attempt to ensure that the volume of the ball remained as constant as possible, regardless of the actual pressure applied. A 5-mm hole was made at the bottom of the lower hemisphere to enable the ball to be inflated to different pressures, without having to remove it from the testing device.

Three tests were performed at different initial pressures of 140, 150, and 160 kPa. For each trial, force was applied to the ball by the arm of the Stentor in successive steps. It was necessary to wait 5 min between each increase in force in order for the Stentor to stabilise the force applied. The force signal from the Stentor was sampled at 100 Hz (a condition imposed by the manufacturer), while the Grip-ball pressure sensor was sampled at 15 Hz. For all subsequent comparisons between the force applied and the pressure observed, force was taken as the mean of the last 100 points (1 s) of the Stentor for each force level, while pressure was taken as the mean of the last 15 points (1 s) produced by the Grip-ball sensor.

A quadratic regression model was calculated to compare the pressure recorded by the Grip-ball with the force applied to the ball.

4. Results

4.1. Validation of the Grip-ball sensor

One hundred and thirty one readings were made across an applied pressure (grip force) range of 0–71 kPa (101–172 kPa measured). The results of the comparison between the Martin Vigorimeter and the Grip-ball sensor are shown in Fig. 4. A linear relationship between the two readings can be observed ($r = 0.997$; 95% confidence interval 0.995–0.998, $p < 0.05$). The linear relationship between the pressure recorded by the Grip-ball sensor and the Vigorimeter manometer was calculated as:

$$\text{Grip-Ball Sensor} = 0.999 * \text{Vigorimeter Manometer} + 0.533 \quad (1)$$

The coefficient of determination was calculated as $R^2 = 0.994$ ($p < 0.05$).

4.2. Relationship between the external force applied and the Grip-ball pressure

Three different initial pressures were used for the Grip-ball (approximately 140, 150, and 160 kPa). Fourteen recordings were made for each of the 140- and 150-kPa initial pressures, while 10 recordings were made for the 160-kPa initial pressure. The forces applied varied from 0–206.5, 0–177.5, and 0–163.0 N for the initial pressures of 140, 150, and 160 kPA, respectively. The results of the validation study for the three different initial pressures can

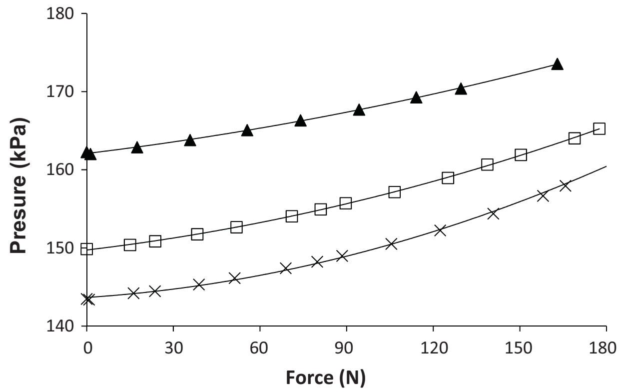

Fig. 5. Comparison between the force applied and the pressure recorded with the Grip-ball for three different initial pressures: (a) 140 kPa (X); (b) 150 kPa (□); (c) 160 kPa (▲).

be seen in Fig. 5. It can be seen that the relationship between force and pressure is curvilinear, regardless of the initial pressure of the ball. A line of best fit was calculated for each initial pressure using a quadratic equation, with data shown in Table 1. The mean squared error for the three initial pressures was 6.18, 7.57, and 9.47 N, for 140, 150, and 160 kPa, respectively. When the current data was used to calculate the force applied using both initial pressure and the pressure measured, grip-force was predicted satisfactorily ($R^2 = 0.97$, standard error of the estimate 10.9 N).

5. Discussion

The aim of the study was to develop a grip-test dynamometer that could be used to measure grip strength without requiring an investigator or clinician to be present. In addition, the aim was also to develop a device that could be used for re-education of the hand and forearm, once again, without requiring anyone other than the user to be present. The device developed, known as the Grip-ball, consists of pressure and temperature sensors and a wireless communication system inside a supple ball. The device was validated in comparison to the closest grip strength dynamometer available, the Martin Vigorimeter, which also measures pressure rather than force. The results of the comparison between the sensors used by the devices were almost identical, after having adjusted for atmospheric pressure (Fig. 4.). It can be inferred from such findings that the Grip-ball sensor and its associated communication system can be used in grip strength measurement.

One of the features of the Grip-ball is the possibility of changing the initial pressure, thus changing the rigidity and dynamics of the grip strength measurement. Accordingly, the second validation study compared the pressure recorded by the Grip-ball to the force applied by a regulated external device, the Stentor, for a range of different initial pressures. In respect to the potential clinical use of such a device, it was necessary to develop predictive equations in order to estimate the force applied to the ball based on the pressure recorded. In such a way, the device could be used for routine grip strength measurement. The predictive errors observed were low, with the coefficient of determination for all three equations close to perfect. However, it is necessary to know the initial pressure in order to use the appropriate equation. A second equation was therefore developed to take into account both the pressure recorded and the initial pressure. Grip-force prediction with this equation gave satisfactory results, with the standard error of the estimate of 10.9 N comparing favourably with the 14 N observed for the Jamar by Harkonen [9]. Such results were achieved with only a relatively small number of observations, and for only three initial pressures. Further investigations will be performed with a prototype industrial version of the Grip-ball across a wider range of initial pressures and forces. The forces applied to the Grip-ball in the present study were limited to 200 N, corresponding to the maximum force produced by our current version of the Stentor. Such a limitation was also due to the method used to hermetically seal the ball, which is not sufficiently strong to deal with large forces. The same is true for the initial pressures, which will be tested across a much larger range. Given that the maximum force one might expect a subject to be able to exert is close to 800 N [10], additional investigations will be performed with the industrial version of the Grip-ball across a wider range of initial pressures and forces. The subsequent validation study will also compare the grip force predicted by the Grip-ball with that recorded using the Jamar, the acknowledged gold standard for grip strength measurement. This study will also compare the results obtained with the Grip-ball in the presence of a trained investigator with those obtained without any supervision. This validation step is necessary before the Grip-ball could be considered acceptable for unsupervised use in the home.

An obvious limitation of the current proof of concept version of the Grip-ball is that only a small range of forces was assessed, up to a maximum of 200 N. The reason that such a small force-range was used was twofold. Firstly, the hermetic sealing of the envelope of the proof of concept version is unable to resist high forces. Secondly, a large force applied to the ball would cause the envelope to come into contact with the electronics inside the ball. Both of these issues will be resolved in the industrial version of the device that is currently under development. The electronics will be miniaturised, while the envelope will be fabricated around the electronic components.

Another limitation of the current prototype version is the low sampling frequency. 15 Hz is not an acceptable frequency for real-time applications or for possible advanced signal processing. That limitation was only due to the prototype electronic circuits. The new version will be designed for a sampling frequency at 100 Hz.

The current paper focused on the capability of the Grip-ball to measure the grip-strength. However, the rapid development of applications related to telerehabilitation and more generally for telehealth systems (see for instance [11] or [12]) opens the way to evaluation or rehabilitation exercises remotely controlled or supervised by a professional. When used at home, the Grip ball could be linked to an entertainment software package to motivate the user as part of their evaluation or re-education. For instance, rather than squeezing a ball repeatedly for ten minutes, a patient could use a "serious game" requiring the ball to be squeezed, with information related to performance readily available to both the user and the healthcare professional.

Table 1
Best-fit quadratic equations for the relationship between force and pressure for different initial pressures of the Grip-ball?

Initial pressure (kPa)	R^2	Standard error	Constant	$b1$	$b2$
140	0.997	4.08	−9078.507	−0.329	110.594
150	0.998	2.81	−10270.917	−0.349	120.812
160	0.999	2.35	−14732.653	−0.443	162.683

Equations are $b1 * \text{pressure}^2 + b2 * \text{pressure} + \text{constant}$.

6. Conclusion and perspectives

A new device, called the Grip-ball has been developed to evaluate grip strength and might be used for hand and forearm re-education. The device, which has been designed for use without the presence of a trained investigator, accurately predicts grip force based on the pressure measured inside the ball. The aim behind the development of the Grip-ball is to enable home-based assessment of grip strength, thus minimising the need to travel to a healthcare professional as part of a regular clinical evaluation or for post-traumatic rehabilitation.

A major feature of the Grip-ball is that it can communicate directly with other electronic devices via Bluetooth, opening up the possibility of more interactive use than standard grip strength devices. This paper has demonstrated the feasibility of the Grip-ball, an innovative grip strength measurement device. Future work will include an objective validation of the Grip-ball compared to the Jamar and the Martin Vigorimeter, both of which are considered to be reference devices. Data will be collected on maximal grip strength for a large population, including children, adults and the elderly. The reliability of the Grip-ball when used without the presence of an investigator will also be assessed.

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Conflict of interest statement

The authors do not have any competing interests.

References

[1] Bohannon RW. Hand-grip dynamometry provides a valid indication of upper extremity strength impairment in home care patients. J Hand Ther 1998;11(4):258–60.
[2] Bohannon RW. Adequacy of simple measures for characterizing impairment in upper limb strength following stroke. Percept Mot Skills 2004;99((3) Pt 1):813–7.
[3] Avlund K, Schroll M, Davidsen M, et al. Maximal isometric muscle strength and functional ability in daily activities among 75-year-old men and women. Scand J Med Sci Sports 1993;4(1):32–40.
[4] Fried LP, Tangen CM, Walston J, et al. Frailty in older adults: evidence for a phenotype. J Gerontol A Biol Sci Med Sci 2001;56(3):M146–57.
[5] Nybo H, Gaist D, Jeune B, et al. Functional status and self-rated health in 2262 nonagenarians: the Danish 1905 Cohort Survey. J Am Geriatr Soc 2001;49(5):601–9.
[6] Schaubert KL, Bohannon RW. Reliability and validity of three strength measures obtained from community-dwelling elderly persons. J Strength Cond Res 2005;19(3):717–20.
[7] Kowanko IC, Knapp MS, Pownall R, et al. Domiciliary self-measurement in the rheumatoid arthritis and the demonstration of circadian rhythmicity. Ann Rheum Dis 1982;41(5):453–5.
[8] J. Duchêne, J.-Y. Hogrel, Dispositif d'évaluation et/ou de renforcement de la force de préhension, FR08/05193, 2008.
[9] Harkonen R, Harju R, Alaranta H. Accuracy of the Jamar dynamometer. J Hand Ther 1993;6(4):259–62.
[10] Mathiowetz V, Wiemer DM, Federman SM. Grip and pinch strength: norms for 6- to 19-year-olds. Am J Occup Ther 1986;40(10): 705–11.
[11] Huijgen BCH, Vollenbroek-Hutten MMR, Zampolini M, et al. Feasibility of a home-based telerehabilitation system compared to usual care: arm/hand function in patients with stroke, traumatic brain injury and multiple sclerosis,. J Telemed Telecare 2008;14(5):249–56.
[12] Popescu VG, Burdea GC, Bouzit M, et al. A virtual-reality-based telerehabilitation system with force feedback," IEEE Trans. Info. Tech Biomed 2000;4(1):45–51.