Journal of Bodywork & Movement Therapies 23 (2019) 739–745

Contents lists available at ScienceDirect

Journal of Bodywork & Movement Therapies

journal homepage: www.elsevier.com/jbmt

Cross-sectional study

The effect of lower leg sensory impulses on the force sense of knee extensor muscles in healthy adults: The accuracy of sense-of-force studies

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ARTICLE INFO

Article history:
Received 1 March 2019
Received in revised form
10 April 2019
Accepted 22 April 2019

Keywords:
Proprioception
Sense of force
Sensory feedback
Knee

ABSTRACT

Background: Producing the target force of a muscle group by using visual feedback and reproducing the same force fully blind are regarded as a common approach for quantifying the sense of force. Force sense error is considered to be the difference between the produced target force and reproduced force. The present study aimed to evaluate the effects of tactile sensory feedback in the lower leg on the perceived magnitude of force sense.
Methods and materials: In this cross-sectional study, 18 healthy men (mean age 24.31 ± 3.94 years) were selected based on a simple randomized method. First, the quantity of force sense error of the knee extensor muscle group was measured before and after manipulating the tactile inputs of the leg. Then, methods A, B, and C were applied to measure force sense errors. In addition, the tactile impulses were manipulated in methods B and C by placing a piece of thick foam between the distal portion of lower leg among the subjects and the dynamometer. The tactile inputs remained intact during method A.
Results: The accuracy of the reproduced target force was significantly affected following the disturbance of tactile inputs in the lower leg in methods B and C, compared to method A ($p < 0.05$).
Conclusion: Altering tactile inputs in the lower leg can affect the force sense of the knee extensor muscles. The received somatosensory inputs across the lower leg can affect the whole process of force perception at this joint.

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1. Background

Proprioception, the ability to comprehend the sense of position, kinesthesia, and force sense, is considered to be the integration of afferent impulses transmitted from cutaneous receptors, joints, and muscular mechanoreceptors to the central nervous system (Riemann et al., 2002; Proske and Gandevia, 2012). The sensations originating from skin, muscles, tendons, fascia, and joint capsules during motion are encoded by mechanically sensitive receptors which innervate body tissues. Afferents from these receptors are projected to the cortex for perceiving the action consciously. A defect in this sense, like any other risk factors, may predispose neuromuscular control to subsequent injuries (Proske and Gandevia, 2012). Human beings can estimate the sense of force or tension as an integral part of the quality of motor control in a precise way. Therefore, employing this sense constantly is necessary for producing a static force during a muscle contraction (Dover and Powers, 2003; Lephart et al., 1998).

Traditionally, there are two fundamental hypotheses for explaining the possible mechanisms responsible for tuning this sense. In the first approach, called “the sense of effort”, the conscious perception of muscle force refers to the corollary discharges of motor commands to the cortex sensory area, or sensorium. The second approach, called “the sense of force theory,” is related to peripheral inputs collected by mechanoreceptors in the muscles, cutaneous tissue, and joints. Although both theories may play a significant role in explaining the perception of muscle force, anecdotal data has indicated that the sense of effort theory is more

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https://doi.org/10.1016/j.jbmt.2019.04.007
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influential, compared the sense of force theory (Proske, 2005; De Serres and Fang, 2004; Cuisinier et al., 2011). On the other hand, the sensory inputs collected from cutaneous receptors can influence the perception of the magnitude in the force produced by the fingers. Most previous studies evaluating the effect of tactile impulses on force senses focused more on the upper limb and hand muscles as their target areas (Scotland et al., 2014; Jones and Piateski, 2006; Monzee et al., 2003; Galie and Jones, 2010). In addition, eliminating the tactile impulse through administering local anesthetic agents, or compromising the sensory impulses by using gloves, were considered as two common approaches used in these studies. Further, the quality of the surface in handled objects could affect the perception of force magnitude among the subjects, as objects with smooth and soft surfaces were perceived as heavier than those with rough exteriors (Jones and Piateski, 2006).

Regarding the measurement of the sense of force, a large number of studies has emphasized the reproduction of a defined level of maximum voluntary isometric contraction (MVIC) (Scotland et al., 2014; Park et al., 2008; Adamo et al., 2012; Khalkhali et al., 2016). For example, in the ipsilateral remembered (IR) method, the target force (TF) should be produced as a defined level of MVIC by using visual feedback first. After a time interval, the same TF should be reproduced on the same side, without any visual feedback. The difference between the target force and the reproduced force is called “force sense error”. However, even in the absence of any visual feedback, the physical contact between the participant's body and the measurement apparatus always generates some kind of tactile feedback in order to disturb the accuracy of the results. Therefore, it is not clear yet whether the measured data reflect the sense of force alone, or the combination of tactile senses and sense of force. Thus, since few studies have been conducted on this issue, especially on the lower limbs, and due to the susceptibility of the knee joint to sports injuries, and the important role of quadriceps muscles in knee joint function, the present study aimed to produce a study that would address the effects of sensory inputs in the lower leg on the perceived magnitude of force sense error in the knee extensor muscle group.

2. Materials and methods

2.1. Subjects

In the present study, 18 healthy male students were selected based a simple randomized method (using RandList 1.2 software). The sample size was calculated based on the preliminary data from the study of Galie and Jones (2010) in which the type I error was 0.05 and the power of the test was equal to 0.8 (Galie and Jones, 2010). Inclusion criteria included engaging in amateur sports activities, age between 20 and 30 years, and BMI between 22 and 25 kg/m^2. Exclusion criteria included having a history of knee pain, fractures within the last six months, a limited range of motion, deformities, arthritis, and any systemic or neurological disorders. To comply with the medico-ethical obligations, all subjects were first briefed on the principle and purpose of the study, and then signed a voluntary consent form in order to be officially registered in this study. The protocol of the study was based on the ethical guidelines of the 1975 Helsinki Declaration. The Ethics Committee of Shahid Beheshti University of Medical Sciences, Tehran, Iran, approved the study protocol (Ethic code: 1391-1-94- 5209, 2014/5/17).

2.2. Experimental set-up

The device used in the present study was specifically designed for measuring the sense of force (Khalkhali et al., 2016). Its dynamometric mechanical arms and backrest were designed to support a 60-degree knee flexion and 10-degree trunk backward extension, respectively. In addition, the gliding seat allowed for moving subjects forward and backward easily among the subjects. Further, the height of the device was adjusted to keep the subjects' feet from touching the floor. Furthermore, two straps were fastened around the thighs and two across their trunks during the test in order to prevent subjects' excessive movement among the subjects. Then, the sensory plates were placed above the medial malleolus and were fixed in position by Velcro straps in order to accommodate the lower leg pressure during the exertion time. At the next stage, the 60-degree knee flexion was confirmed by an ordinary goniometer. Korean-manufactured load cells, Cp 500 N model, were used in the present study. The particular positioning of these cells on dynamometric mechanical arms was considered as an advantage for the assessor, allowing for measurements from all desired angles. Furthermore, a designated USB port with 16- bit resolution and a speed of 64 samples per second connected the load cells to the device computer, facilitating a swift sampling process. The device indicated a high reliability ($r = 0.73–0.81$, $SEM = 0.38$) for measuring the force sense of the knee extensor muscles (Khalkhali et al., 2016; Kim et al., 2014).

3. Procedure

In order to evaluate the effects of leg sensory inputs on the force sense in knee joint, the protocol of the present study was divided into selecting a maximum voluntary isometric contraction (MVIC) and identifying a standard target force (TF) level as 50% of the detected MVIC. In the first section, 10 sets of force matching tasks were randomly allocated with different time intervals between producing and reproducing trials to find the optimum time interval with the most accurate sense of force. In the second section, three force sense-measuring methods (A, B, and C) were compared for each subject in random order. In this section, tactile inputs, at the contact area between the dynamometer and lower leg, were manipulated during methods B and C by using a thick foam pad.

3.1. Section 1

3.1.1. Identifying MVIC and TF

In order to measure the MVIC, three strong voluntary isometric contractions were recorded for dominant knee extensor muscle group. Each of these verbally prompted contractions lasted for 5 s, and the highest one was taken as the subject's MVIC. A 60- second pause was taken between every two contraction attempts, and 50% of the recorded MVIC was regarded as a desired target force within this section (Scotland et al., 2014; Adamo et al., 2012; Salahzadeh et al., 2013). Then, the subjects were given a 5-min rest before moving to the force-matching tasks in this section.

3.1.2. Force-matching tasks

In this section, 10 sets of two force matching tasks were selected for the knee extensor muscle group. Each task included one producing and one reproducing phase in order to achieve the defined level of TF. In each set, a similar time interval was used between the production and reproduction phase. A 3-min pause was taken between the tasks. The assigned time interval for each set was unique and randomly ordered from a range of 5, 10, 15, 20, 30, 40, 60, 80,100 and 120 s. No attempt was made to manipulate the tactile inputs during this part of the study, and the subjects received a 5-min break after completing each set. This section was completed two weeks before the second section.

3.2. Section 2

3.2.1. Method A: force sense measurement without manipulating tactile inputs

The method included three force matching-tasks on the subject's dominant side, without any interference in tactile inputs. Each task included one production followed by a reproduction trial, which was repeated for three times with a 3-min pause. In the production trial, 50% of MVIC as target force was produced by using visual feedback. After 20 s, the subjects were asked to reproduce the target force without any visual feedback. Both contractions should be held for 8 s (Park et al., 2008; Salahzadeh et al., 2013; Adamo et al., 2007). In addition, they received a 3-min break at the end of each task and a 5-min break before starting the next methods B or C. One physiotherapist was in the charge of the entire assessment process. Further, the subjects were asked to alert the assessor when they reached their assumed target force (Fig. 1).

In order to measure the force sense error, the difference between the target force and reproduced force was calculated, along with the absolute, constant, and variable errors for each subject.

3.2.2. Methods B and C: force sense measurement by manipulating the tactile inputs

During these methods, the same procedure as method A was performed for the production and reproduction trials. In addition, three force-matching tasks were used for each of these methods. The tactile inputs were manipulated by placing a 16-cm thick foam pad between the subjects' lower leg and the dynamometer during the reproducing trial of method B and the producing trial of method C. By using the foam pad, the knee joint angle changed slightly, which was readjusted to the predetermined knee angle of 60 °.

4. Data analysis

A purpose-built USB port received analogue inputs from the load cells and transmitted them to the device computer as encoded digital output. Intercommunication between the analogue and digital components of the device were established using C++ software, and Qt package was used for visual graphics and provide visual feedback. In addition, MATLAB software was used for analyzing trend data, calculating mean, and classifying the data. Further, the force sense error was estimated in three different classes of observational errors, including constant, variable and absolute errors. Based on the constant error [CE = (xi-T)/n; xi = estimated force, T = TF, n = number of estimation], a simple difference was observed between the estimated and defined TF. Furthermore, all estimated contractions above or below the desired TF level were marked with a positive (overshoot) and negative (undershoot) sign, respectively. Additionally, the absolute error [AE = |xi-T|/n; xi = estimated force, T = TF, n = number of estimation] was calculated to measure the overall accuracy in the performance among the subjects, which is the average absolute deviation between the estimated force and actual TF (Salahzadeh et al., 2013; Boisgontier and Nougier, 2013; Docherty et al., 2006; Vuillerme and Boisgontier, 2009). In the next stage, the variable error [VE = $\sqrt{}$ å (xi - M) ^{2}/n); Xi = estimated force, M = mean of the three estimated forces, n = number of estimation] was computed to measure the consistency in the estimated force or deviation from the standard of the mean in the three repeated tasks for each method, which reflected the degree of inconsistency across individual responses to a given stimulus (Salahzadeh et al., 2013; Boisgontier and Nougier, 2013). In order to normalize the error values as a fair percentage of the recorded MVICs for all subjects, the error of the mean for each method was divided by the MVIC and the result was multiplied by 100 [The Error of the Mean/MVIC × 100] (Scotland et al., 2014; Adamo et al., 2012; Kues et al., 1992). SPSS software (version 18) was used for data analysis. The data distribution was evaluated by using the Shapiro-Wilk test, which indicated an acceptable minimum score of 0.096. In addition, a repeated measure ANOVA with the significance level of $P \leq 0.05$ was used to compare the data under different conditions in Section 2, as well as comparing the tested time intervals in Section 1 (Fig. 2).

5. Results

The subjects' demographic characteristics and the mean values of MVIC in the extensor muscle group are reflected in Table 1.

Under the divergent conditions, the repeated measures of analysis variance revealed:

1) No significant difference of sense of force error was observed across the trials with the time interval from 5 s up to 30 s. With

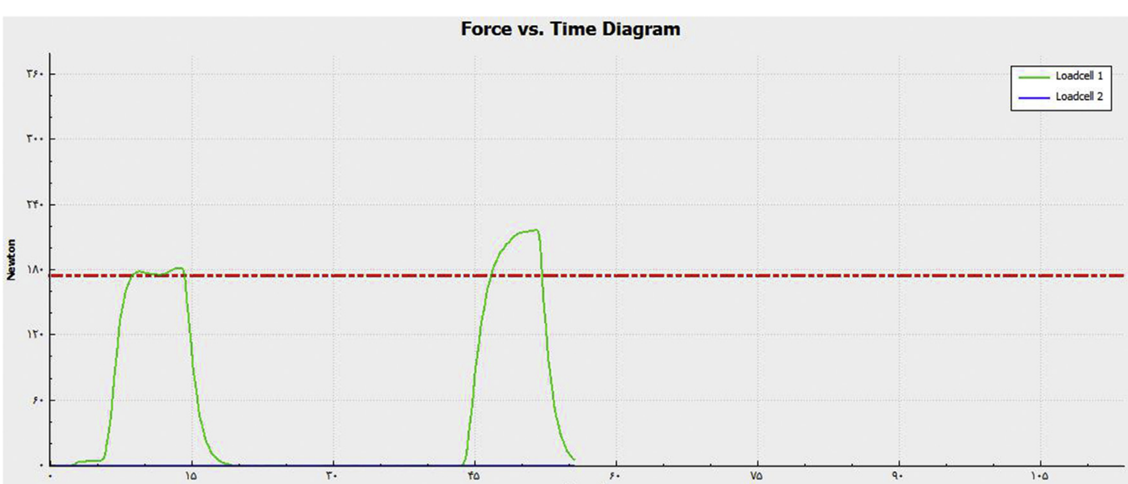

Fig. 1. Phase 1) force production phase (producing the target force with visual feedback). Phase 2) 20-s rest interval. Phase 3) force reproduction phase without visual feedback. The red dotted line indicates the desired target force = 50% of MVIC. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

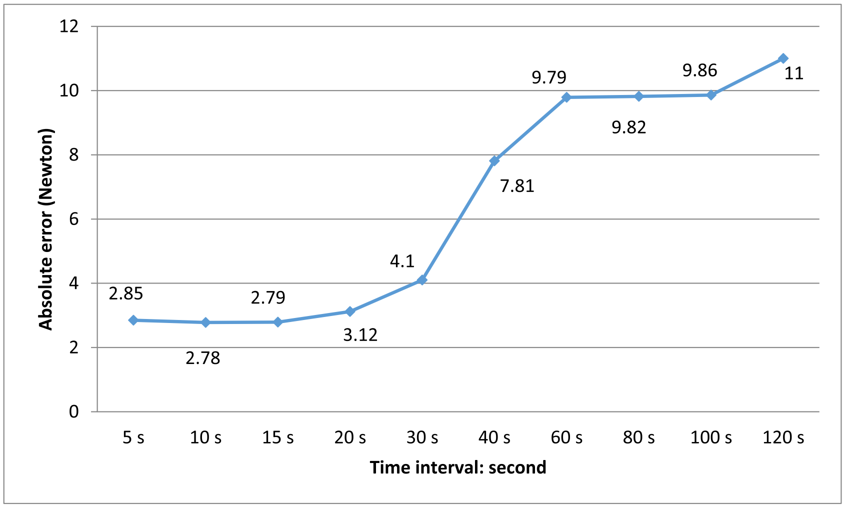

Fig. 2. Absolute error (AE) of force sense at different time intervals.

Table 1
Participants' demographic characteristics and the mean values of maximum voluntary isometric contraction in the right knee extensor muscle group.

Variable	Variable scales/Levels	Mean ± SD
Age	Year	24.31 ± 3.94
Height	Cm	174.93 ± 3.35
Weight	Kg	70.12 ± 6.92
BMI	Kg/m^2	22.89 ± 1.86
MVIC[a] (knee extensor muscles)	Section 1	302.48 ± 41.63
	Section 2	298.77 ± 43.65

[a] MVIC: maximum voluntary isometric contraction.

intervals longer than 30 s, the sense of force error showed higher values progressively ($p < 0.01$) (Table 2).

2) A significant difference of all the three classes of force sense error was seen between methods A and either B or C ($p \leq 0.05$) (Table 3).
3) There was a significant contrast between the mean values of the constant error between methods B and C ($p \leq 0.05$) (Fig. 3).

As illustrated in Fig. 3, no significant difference was observed between the methods B and C in terms of their variable and absolute error mean values ($P > 0.05$).

6. Discussion

The present study aimed to select an appropriate time interval between the produced and reproduced phases and to evaluate the effects of different time intervals on the force sense error. Based on the results, piloting the force-matching tasks seemed to be more relevant when it was reported that placing and removing the foam pad between the producing and reproducing phase last 15–20 s, as required in Methods B and C. Therefore, based on the range of time intervals examined in Section 1, a 20-s pause was determined as an appropriate interval for the rest of the study, which give the assessor enough time to adjust the foam pad in the device without compromising results.

Table 2
Absolute error (AE) values at different time intervals (p-values generated by comparing all the time intervals and 5 s interval).

Producing/reproducing time interval	Absolute error (Newton) Mean ± SD	P-value
5 s	2.85 ± 1.26	–
10 s	2.78 ± 1.21	0.888
15 s	2.79 ± 1.38	0.871
20 s	3.12 ± 1.67	0.591
30 s	4.10 ± 2.18	0.062
40 s	7.81 ± 3.84	0.002 *
60 s	9.79 ± 4.39	0.000 *
80 s	9.82 ± 4.63	0.000 *
100 s	9.86 ± 4.56	0.000 *
120 s	11.00 ± 3.32	0.000 *

*($p < 0.05$).

Table 3
Mean ± SD of force sense error (Newton) in section 2.

Method	VE Mean ± SD	CE Mean ± SD	AE Mean ± SD
A	1.87 ± 1.07	2.09 ± 1.44	3.09 ± 1.57
B	3.44 ± 1.69	6.99 ± 3.14	7.79 ± 2.53
C	3.43 ± 1.73	−5.44 ± 3.59	6.70 ± 2.87

Absolute error (AE), Variable error (VE), and Constant error (CE).

In addition, the results indicated how lower leg tactile feedback could influence the force sense of the knee extensor muscle group. Each of three classes related to force sense error including CE, VE, and AE could present significant differences between the errors under the normal and manipulated conditions. However, except for the case of the CE, no difference was reported between the methods B and C regarding the results of absolute errors and the variable errors.

Furthermore, placing a foam pad on a pressure contact point between the subjects' lower leg and the device dynamometer disturbed the comprehension of sensory impulses, and accordingly the accuracy of the force sense. Thus, we could find the reasons for a significant difference between the methods B and C in the calculated CE, which can be expressed as over- and underestimations for these methods, respectively.

Regarding method B, pressing against the foam pad during the reproducing phase could simply mislead the subjects by exerting more force unintentionally, while they made a lot of efforts to exert the same level of target force as they did in the producing phase. Contrarily, the disturbance of the sensory inputs during the producing phase in method C was consistent with the subjects' perceptions of the actual exerted contraction, which was then translated into an insufficient effort during the reproducing phase unintentionally.

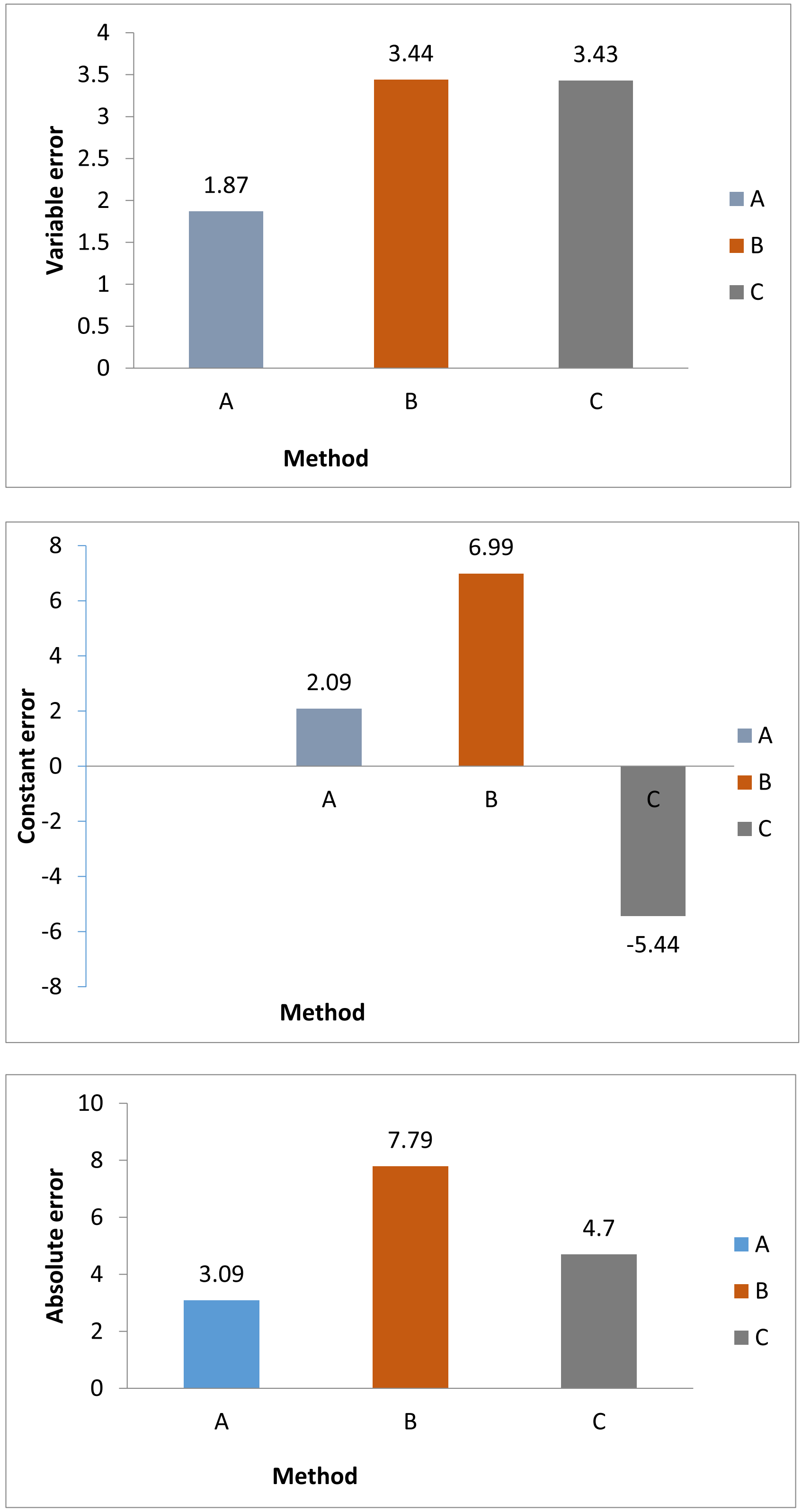

Fig. 3. Absolute error (AE), Variable error (VE) and Constant error (CE) values in section 2. A: no tactile manipulation, B: with tactile manipulation at production phase, C: with tactile manipulation at reproduction phase.

The results of the present study are in line with those of Jones and Piateski (2006), which studied the manipulated sensory inputs of the dominant arm by a three-mm thick splint and its effect on reproduced target force in the opposite side. Based on the results, the underestimated reproduced target force of the index finger and elbow joint was related to the manipulated tactile inputs during the producing phase (Jones and Piateski, 2006). However, some other force-matching studies related to upper limbs supported the reproducing of a larger force or overestimation by the subjects while attempts were made to match the reproduced force with an externally applied target force or weight (Walsh et al., 2011). In another study, Tremblay et al. (2001) reported the influence of local cooling on the proprioception accuracy in the quadriceps muscle and indicated a discriminatory response in favor of detecting larger weights such as 0.4 or 0.5 Kg, compared to lighter weights like 0.11 or 0.28 Kg. However, lack of any significant difference in response to similar weights before and after using local cooling failed to attribute any proprioceptive disturbance to the sensory manipulation by cooling (Tremblay et al., 2001). It seems that a similar sensory condition for producing and reproducing target force task casts doubt on the results. Based on the results in the present study, the perception of the force sense appears to rely heavily on the information supplied by cutaneous mechanoreceptors. Augurelle et al. (2003) suggested that the hand numbness can influence the perceived force or weight magnitude experienced by the subjects. In addition, a decrease occurred in the recorded MVIC to the diminished sensory feedback under these conditions (Augurelle et al., 2003). The results are consistent with those of the present study. In another study, Kilbreath et al. (1997) evaluated the changes in the perception of force magnitude after desensitizing the fingers. The mixed results for the bilateral distal interphalangeal joint flexors indicated an increase in the sense of heaviness for the thumb and index finger by 41 and 13%, respectively. However, a decrease in the sense of heaviness could be confirmed for the ring and little fingers by 14 and 21%, respectively (Kilbreath et al., 1997). Further, the errors in the perceived heaviness were related to motor command signals which could trigger some net facilitatory or inhibitory reflexes from digital neural endings into their corresponding motor neurons. The increase and decrease in the perceived heaviness seem to be considered as the inevitable outcomes of activated facilitatory and inhibitory reflexes, respectively. In another force-matching study, Monzee et al. (2003) analyzed the effect of surface quality, along with anesthetic agents on the thumb and index finger. By considering the target force of 0.5, 1, 1.5, and 2 N, the results indicated less bias in force-reproducing before and after using anesthesia when rough surfaces are involved. However, the error demonstrated higher values after utilizing the anesthetic agents. Thus, disturbed sensory impulses compromised the coordination and force control process which could not simply be offset by a solo sense of effort (Monzee et al., 2003).

Furthermore, Galie and Jones (2010) focused on the influence of temperature on the force control of the index finger. The result indicated that a rise in temperature from 24 to 32 °C cannot produce a significant effect on the range of the perceived force from 0.1 to 6 N. Although the effect of temperature was not considered in this study, selecting a different range of temperature and target force may lead to different results (Galie and Jones, 2010). In addition, Haupenthal et al. (2015) analyzed the ability of the ankle-dorsiflexor muscles to replicate isometric force after a period of skin cooling. The amount of error was more after cooling and at 50% of MVIC. Further, skin cooling decreased the proprioceptive ability of the ankle dorsiflexor muscles to replicate isometric force. The findings suggest that somatosensory changes can affect the accuracy of force sense (Haupenthal et al., 2015). Based on the results in the present study, tactile inputs can interfere with our perception of the sense of force, and employing different measurement designs with the different tactile stimulus can lead to different results. For example, different results may be obtained after measuring the force sense during open or closed chain settings due to different sensory inputs. During close kinematic chain settings, the strong pressure on the sole of the foot provides more sensory feedback which can change the sense of force, compared to the open chain settings. However, the results of this study cannot be directly compared with others since few studies have been reported on the accuracy of lower limb force matching tasks, especially under the different sensory conditions. Thus, as force sense mostly relies on the sense of effort and sensory receptors for further adjustments, the role of cutaneous mechanoreceptors such as touch and pressure should be considered in future studies. Additionally, 18 normal volunteers participated in the present. Therefore, a larger sample size can be considered in other studies. It is plausible that different results may be obtained if patients are recruited with different musculoskeletal disorders. However, the inclusion of the time interval between producing and reproducing force as a factor which could affect the accuracy of the sense of force is regarded as one of the advantages of this study.

7. Conclusion

Based on the results, different somatosensory conditions can affect the accuracy of force sense as an integral part of proprioception. In other words, defects in sensory input play a significant role on force sense which necessitates the therapist's careful attention while evaluating the patho-biomechanics of injuries or conducting the physical examination.

Authors' contribution

Bahram Amirshakeri directed the implementation, design, and conduction of the study. Minoo Khalkhali Zavieh and Asghar Rezasoltani contributed to the design of the study and supervised all of the experiments. We also thank Khosro Khademi Kalantari, and Alireza Akbarzadeh Baghban for their recommendations. All authors read, critically revised, and approved the final manuscript.

Conflicts of interest

All authors declare no conflicts of interest.

Funding/support

The present project was supported by Shahid Beheshti University of Medical Sciences.

Acknowledgments

The authors would like to thank Vahab Nedaey, Ghadam Ali Talebi, Amin Badri and Mohammad Balazadeh for their help in completing the instrument set-up, and all of the subjects in this project.

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