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The Effect of a Previous Strain Injury on Regional Neuromuscular Activation Within the Rectus Femoris

by
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The rectus femoris (RF) has a region-specific functional role; that is, the proximal region of the RF contributes more than the middle and distal regions during hip flexion. This study aimed to investigate whether RF strain injury affected the region-specific functional role of the muscle. We studied seven soccer players with a history of unilateral RF strain injury. Injury data were obtained from a questionnaire survey and magnetic resonance imaging (MRI). Multichannel surface electromyographic (SEMG) signals were recorded from the proximal to distal regions of the RF with 24 electrodes during isometric knee extension and hip flexion. The SEMG signals of each channel during hip flexion were normalised by those during knee extension for the injured and non-injured RF (HF/KE), and compared among the proximal, middle, and distal regions. Six RF strain injuries showed a low signal area in MRI. There was no significant difference in muscle strength between the injured and non-injured RF. While the HF/KE in the proximal region was significantly higher than those in the middle and distal regions in the non-injured RF, a difference in the HF/KE was seen only between the proximal and distal regions of the injured RF. Furthermore, the HF/KE of the most proximal channel in the injured RF was significantly lower than that in the non-injured RF. However, there was no significant difference between injured and non-injured areas in the HF/KE. Our findings suggest that the region-specific functional role of the RF muscle is partly affected by RF strain injury.

Key words: rectus femoris, strain injury, electromyography, physiology, sports medicine.

Introduction

Rectus femoris (RF) strain injury is the most common quadriceps strain injury (Cross et al., 2004). Thigh strain injuries including the hamstring and RF are most common among professional soccer players (Hawkins et al., 2001). Athletes with a prior quadriceps strain injury are at an increased risk for a recurrent injury (Orchard, 2001; Wittstein et al., 2011). RF strain injury occurs during actions such as kicking or sprinting (Gyftopoulos et al., 2008; Renstrom, 1992). In a study of the magnetic resonance imaging (MRI) features of RF strain injury, the coronal T1-weighted image showed a low signal surrounding the deep intramuscular tendon, representing a pseudocyst (Gyftopoulos et al., 2008). Most RF strain injuries occur in the proximal third of the muscle (Pasta et al., 2010). The RF has two heads with two separate tendons of origin (Hasselman et al., 1995). The direct head originates from the anterior inferior iliac spine, and the indirect head originates from the acetabulum. The tendon of the direct head is usually broad and flat, and located on the anterior surface of the muscle. The tendon of the indirect

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head continues distal to the acetabulum as a tendon within the muscle belly, such that the indirect head has the appearance of a muscle within a muscle. The tendon of the indirect head continues to approximately two-third of the length of the muscle (Gyftopoulos et al., 2008; Hasselman et al., 1995; Pasta et al., 2010). This complex musculotendinous architecture is one of the factors contributing to muscle strain injury (Hasselman et al., 1995; Hughes et al., 1995; Kary, 2010).

In addition, the RF is innervated by two separate motor nerve branches located in the proximal and distal regions of the muscle (Sung et al., 2003; Yang and Morris, 1999). This means that two different parts of the RF muscle can be regulated by different neural strategies. By using multichannel surface electromyography (SEMG), Watanabe and colleagues (2012) found that the RF had a region-specific functional role. This region-specific functional role means that the proximal region of the RF had a higher SEMG amplitude than the middle and distal regions during hip flexion (Watanabe et al., 2012). In addition, another study showed a similar tendency (Miyamoto et al., 2012). Therefore, Watanabe and colleagues (2012) suggested that the proximal and distal regions had different biomechanical functional roles (Watanabe et al., 2012, 2013). Moreover, they found that this region-specific functional role of the RF was used during actual human movements such as walking (Watanabe et al., 2014, 2016b) and pedalling (Watanabe et al., 2015).

Recently, the influence of neuronal function on muscle strain injury has received research attention. Eccentric contractions with fast angular velocities induce functional and structural damage in innervating nerves in rats (Kouzaki et al., 2016; Lee et al., 2014). In humans, Opar et al. (2012) found that the SEMG activity of a biceps femoris (BF) long head with a previous strain injury was lower than that of the contralateral non-injured leg. Although the SEMG activity of the BF is affected by strain injury, the BF does not have a region-specific functional role (Watanabe et al., 2016a). RF strain injury might have a large influence on the nerve function of the RF because the RF has a more complex neural function than the BF. Clarifying the relation between the region-specific functional role of the RF and RF strain

injury may help in strain injury prevention and rehabilitation.

Therefore, the aim of this study was to investigate whether RF strain injury affected the region-specific functional role of the muscle. We hypothesised that the SEMG activity of the injured RF was lower than that of the non-injured RF. In addition, RF strain injury disrupted the region-specific functional role of the muscle.

Methods

Participants

The participants were recruited from a soccer team belonging to the Japan University Football Association. We studied seven soccer players with a history of unilateral RF strain injury (age, 19.6 ± 1.8 years; body height, 171.9 ± 5.4 cm; body mass, 65.6 ± 6.3 kg; sport-related experience, 14.1 ± 2.3 years). The right leg was dominant in all participants. The dominant leg was defined as the leg used for kicking. The present study protocol was approved by the ethics committee of the Nippon Sport Science University. All athletes provided written informed consent before participation. Information about the purpose of the study, potential risks, and protection of the rights of the participants was provided to all athletes.

Questionnaire

The data of physical characteristics and RF strain injury were collected through a questionnaire survey. There are two primary mechanisms of RF muscle injury. Indirect muscle injuries are caused without the influence of a direct external trauma, whereas direct muscle injuries are caused by a blunt or sharp external force. Indirect injuries have therefore been previously defined as muscle strains and direct injuries as contusions (Ueblacker et al., 2015). In this study, we modified the definition of injury in reference to the previous research (Rossler et al., 2016). RF strain injury was defined as indirect muscle injury that required medical attention and/or absence from subsequent training sessions or matches. In addition, we defined the injured RF as the leg with a history of RF strain injury and the non-injured RF as the leg with no history of RF strain injury.

MRI

MRI (AIRIS II, Hitachi, Japan) was performed using a 0.3-T scanner with a 40-cm-

diameter extremity coil in the supine position. The field of view was 32 cm and the matrix was 256 × 256. Coronal T1-weighted images (reception time/echo time, 1000 ms/20 ms) were obtained. The scan range was 20 cm around the injury site that the participants indicated in the questionnaire. The slice thickness was 10 mm. The MRI scans were examined by a single highly experienced orthopedic surgeon who specialized in muscle injuries.

Experimental design

In this study, we modified the methods according to previous studies (Watanabe et al., 2012, 2013). The participants performed isometric maximal voluntary contraction (MVC) of knee extension and hip flexion in the injured RF. During each MVC, multichannel SEMG signals were recorded from the injured RF muscle. The non-injured RF was analysed in the same manner.

MVC of knee extension and hip flexion

Isometric knee extension and hip flexion strength were measured with a Biodex System 3 dynamometer (Biodex Inc., USA). During MVC, the trunk was fixed to the dynamometer. The position of the hip and knee was flexed at 90°. After the warm-up and practice MVC, participants performed four tasks. First, knee extension and hip flexion in the ipsilateral side were performed at random. Second, the tasks were performed with the opposite leg, also at random and in the same manner. Moreover, these tasks were performed at random for both the injured RF and the non-injured RF.

The MVC involved a gradual increase in the knee extension or hip flexion force exerted from baseline to maximum in 2–3 s, and then sustained at maximum force for 2 s. Constant and identical verbal encouragements were provided during the test. The participants performed at least two MVC trials with ≥ 2 min rest between trials for both tasks. The higher MVC torque was used for further analysis.

Multichannel SEMG recording

Watanabe et al. (2012, 2013) reported that the region-specific functional role of the RF was mainly demonstrated along a longitudinal line of the muscle. Thus, during each MVC, we recorded SEMG signals from the RF by using 24 electrodes arranged in one row (inter-electrode distance: 10 mm; ELSCH16, OT Bioelettronica, Italy) (Figure 1).

Conductive gel was inserted into the cavities of the electrodes to assure proper skin contact. Before attaching the electrodes, the skin was shaved, abraded, and cleaned with alcohol. To determine the electrode location, the edge of the superficial region of the RF was identified using ultrasonography (SSD-3500, Aloka, Japan). Marks were applied to the skin surface above the border between the RF and other neighbouring muscles (i.e., vastus lateralis, vastus medialis, sartorius, and tensor fasciae latae), by a waterproof pen. Consequently, the superficial regions of the RF were surrounded by marks on the skin, and the electrodes were attached within the markings. The electrodes were placed on the longitudinal axis of the RF along a line between the anterior superior iliac spine and the superior edge of the patella. The line between the anterior superior iliac spine and the superior edge of the patella was defined as the longitudinal line of the RF from anatomical data of the human RF (Sung et al., 2003; Yang and Morris, 1999). The center of the sixth and seventh electrodes from the proximal end was placed at the proximal third of the longitudinal line of the RF (Figure 1). The mean length of the longitudinal axis of the RF muscle was 43.3 ± 3.8 cm. The range of the RF muscle where an SEMG signal was detected was approximately 19-75% of its longitudinal line. A reference electrode was placed at the head of the fibula.

Monopolar SEMG signals were amplified by a factor of 1000, sampled at 2048 Hz with an eighth-order Bessel band-pass filter at 10–500 Hz (anti-aliasing filter), and converted to the digital form using a 12-bit analogue-to-digital converter (EMG-USB 2, OT Bioelettronica). The recorded monopolar SEMG signals were transferred into analysis software (OT BioLab, OT Bioelettronica). In addition, 23 bipolar SEMG signals were calculated from the electrode pairs between the neighbour electrodes. Root mean square (RMS) values were calculated from the bipolar SEMG signals that were sampled over 1-s epochs during the MVC. To investigate the region-specific functional role of the injured and non-injured RF, 23 RMS values of the hip flexion in the injured and non-injured RF were normalised by those of the knee extension for each electrode pair (HF/KE). The 23 HF/KE values were equally divided into three regions as described in previous studies (Watanabe et al., 2012, 2013)

(Figure 1). The reason for utilizing similar methods to previous studies was to compare control groups between studies and assess the suitability of this method for regional RF assessment. We calculated the average HF/KE of the injured RF and the non-injured RF in each region. Additionally, we calculated the affected side/unaffected side ratio of each channel (Ch) for each subject. To clarify the relationship of injured regions and the HF/KE, all Ch of participants who showed a low signal area in MRI were divided into the injured Ch and the non-injured Ch. The injured Ch was defined as the region with the same signal level as the pseudocyst that was seen with MRI for each subject. The other regions were defined as the non-injured Ch. We calculated the average values of the affected side/unaffected side ratio in the injured Ch and the non-injured Ch.

Statistics

All data are presented as means and standard deviations. To compare the MVC between the injured RF and the non-injured RF, the Mann-Whitney U-test was used to detect statistical differences. The HF/KE of the injured RF and the non-injured RF were compared among three regions using the Mann-Whitney U-test with Bonferroni correction. With the Mann-Whitney U-test, statistical differences of the HF/KE in each Ch between the injured RF and the non-injured RF were detected. Furthermore, to compare the affected side/unaffected side ratio between the injured Ch and the non-injured Ch, the Mann-Whitney U-test was also used. A p value <0.05 was considered statistically significant. All statistical analyses were performed using IBM SPSS Statistics 23 software for Windows (SPSS IBM; Japan Inc., Tokyo, Japan).

Results

Data of RF strain injury

The strain injuries in four and three participants were induced by kicking and sprinting actions, respectively. Whereas two participants had the strain injury in the non-dominant leg, five participants had the strain injury in the dominant leg. All RF strain injuries occurred in the proximal half, according to the questionnaire. All participants were able to return to their pre-injury competitive level. However, three participants experienced tightness of the thigh, fatigability of the quadriceps muscle, and both, respectively. The mean time from the

initial injury to the study was 40.3 months (range, 12–96 months). Six participants underwent rehabilitation at different medical clinics. One participant did not complete rehabilitation. The mean duration of absence in practice or competition was 13.1 weeks (range, 4-16 weeks). In addition, there was no history of other strain injuries including bilateral hamstring injuries.

From the MRI results, in six of the seven RF strain injuries, the axial T1-weighted image showed a low signal area. In four RF strain injuries, a low signal area was seen in the deep intramuscular tendon. In two RF strain injuries, a low signal area was noted in the posterior myofascial junction of the RF. In one of the seven RF strain injuries, the axial T1-weighted image did not show a low signal. The longitudinal range of the injured region in the six participants who showed a low signal area in MRI was approximately 6 cm (range, 3–10 cm). In one RF strain injury, the low signal area was seen at the proximal and middle regions. In four RF strain injuries, the low signal area was observed from across the proximal to the middle region. In five particpants, the injured area was Ch 8. In four participants, the injured areas were Ch 5, Ch 6, Ch 7, Ch 9, and Ch 10.

MVC torque

The MVC torque of hip flexion was 164.1 ± 35.6 N·m in the injured RF and 173.3 ± 24.8 N·m in the non-injured RF. The MVC torque of knee extension was 244.6 ± 33.7 N·m in the injured RF and 250.6 ± 42.0 N·m in the non-injured RF. There was no significant difference in the MVC torque of hip flexion and knee extension between the injured RF and the non-injured RF.

Multichannel SEMG

The HF/KE at three regions in the injured RF is shown in Figure 2a. There was a significant difference between the proximal (1.06 ± 0.25) and distal (0.61 ± 0.20) regions ($p < 0.05$). The HF/KE at three regions in the non-injured RF is shown in Figure 2b. There were significant differences between the proximal (1.12 ± 0.26) and middle (0.80 ± 0.22), as well as between the proximal (1.12 ± 0.26) and distal (0.68 ± 0.17) regions ($p < 0.05$).

The HF/KE of each Ch in the injured and non-injured RF is shown in Figure 3. Only Ch 1 showed a significant difference in the HF/KE between the injured RF (1.02 ± 0.30) and the non-injured RF (1.44 ± 0.34) ($p < 0.05$).
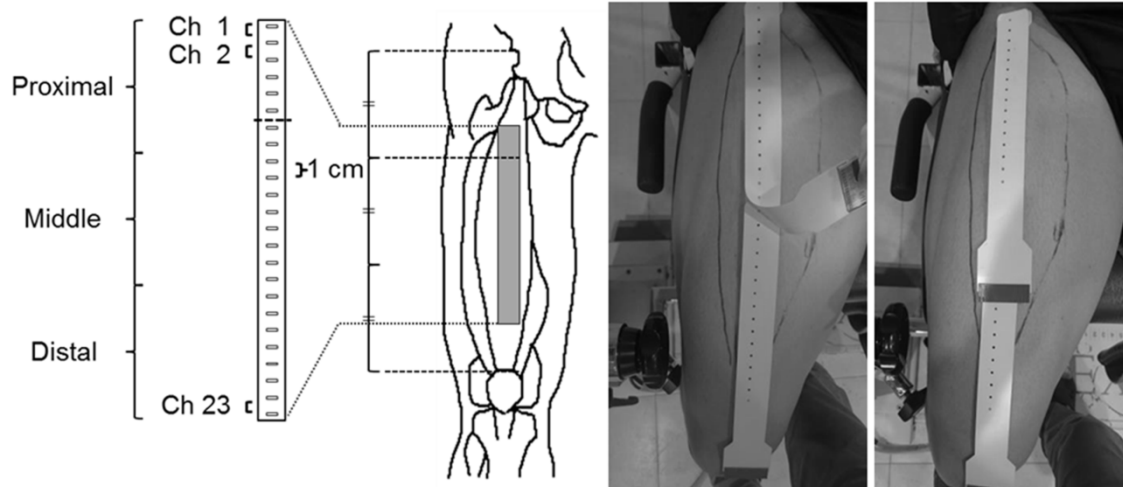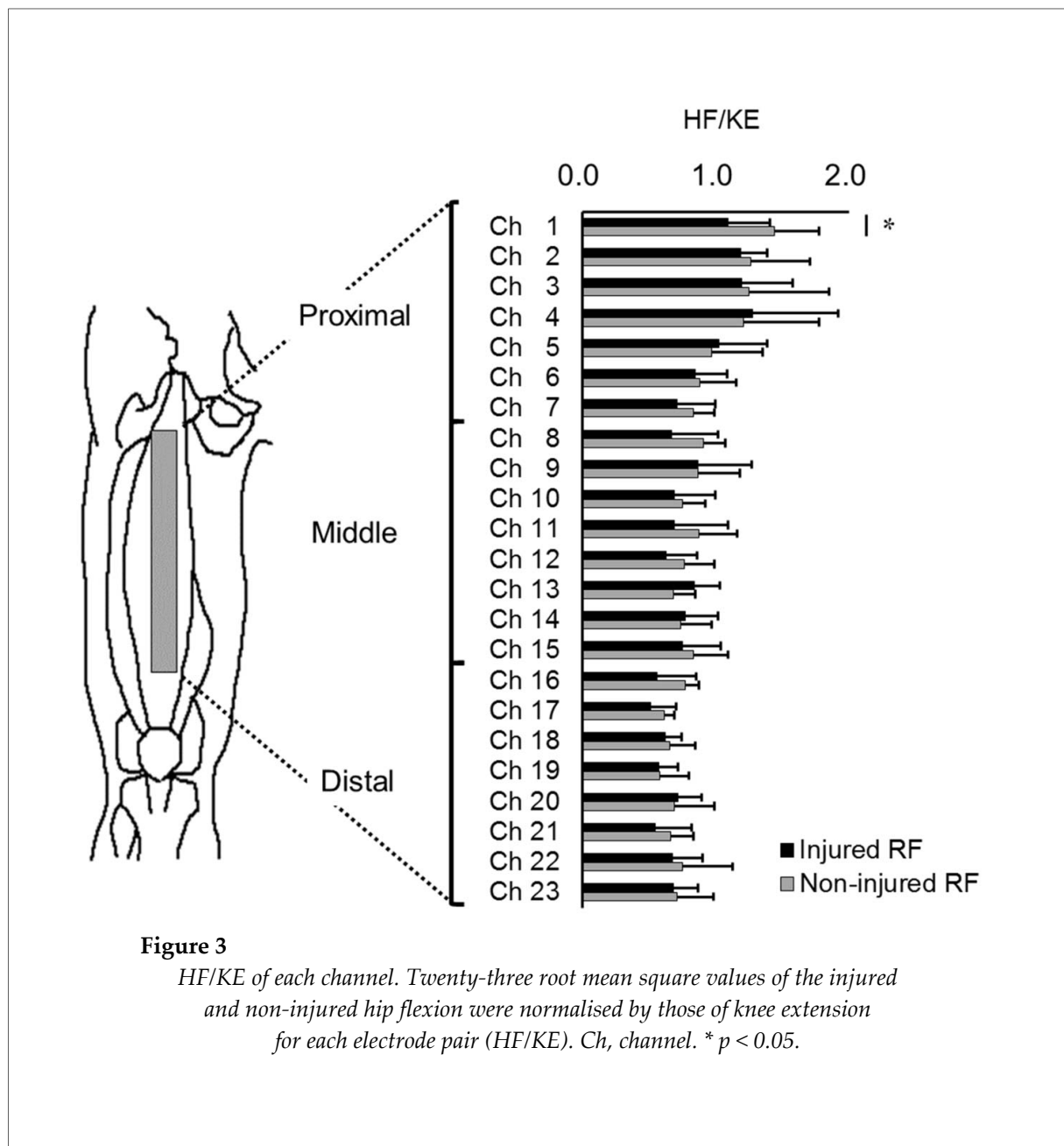
Figure 1

Locations of the 24 electrodes used for the rectus femoris muscle.
Twenty-three bipolar SEMG signals were calculated from the electrode pairs between
the neighbour electrodes. Twenty-three channels were equally
divided into three regions. Ch, channel.
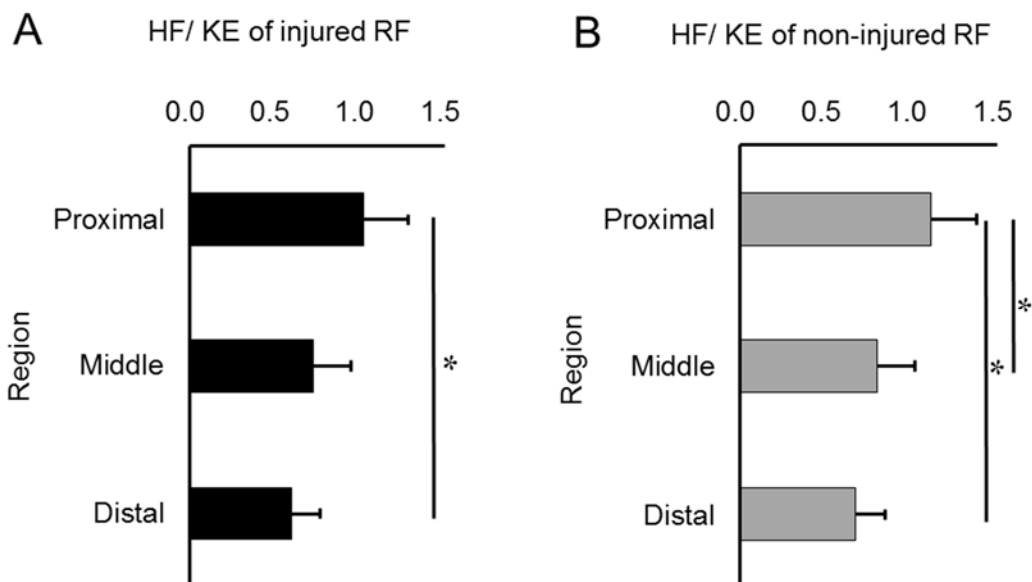
Figure 2

HF/KE of regions. Twenty-three root mean square values of the injured and non-injured
hip flexion were normalised by those of knee extension for each electrode pair (HF/KE).
The 23 HF/KE were equally divided into three regions. The left graph shows the injured
*RF (a), and the right graph shows the non-injured RF (b). * $p < 0.05$.*

Figure 3

*HF/KE of each channel. Twenty-three root mean square values of the injured
and non-injured hip flexion were normalised by those of knee extension
for each electrode pair (HF/KE). Ch, channel. * p < 0.05.*

From the MRI results, there were 38 injured Ch and 100 non-injured Ch in six participants. In the affected side/unaffected side ratio, there was no significant difference between the injured Ch (108.4 ± 33.2%) and the non-injured Ch (100.9 ± 32.1%).

Discussion

In this study, a different distribution pattern of the HF/KE was found between the non-injured RF and the injured RF (Figure 3). As we hypothesised, the region-specific functional role of the RF might be affected by strain injury of the muscle.

In this study, six of the seven RF strain injuries showed a low signal area in MRI. Hasselman et al. (1995) performed cadaveric dissection of the RF with strain injury. They found that serous fluid from a hematoma may remain within the connective tissue sheath, creating a pseudocyst in the intramuscular tendon. Although six subjects returned to their sport, the injured muscle might be considered to be incompletely healed. Athletes with a prior RF strain injury are at an increased risk of re-injury (Orchard, 2001; Wittstein, et al., 2011). Therefore, those six subjects might have a higher risk for a

recurrent injury.

MVC torque

In this study, there was no difference in the MVC torque of hip flexion and knee extension between the injured RF and the non-injured RF. In RF strain injury, persistent disabling symptoms are extremely rare (Wittstein et al., 2011). Return to sport requires recovery of muscle strength. Although muscle strength in the injured RF had been recovered, there is a possibility that another muscle (i.e., psoas) compensated for the RF. Therefore, further studies are needed.

Multichannel SEMG

Concerning the HF/KE of the non-injured RF, the proximal region had a significantly higher value than the middle and distal regions (Figure 2b). Watanabe et al. (2012) clarified that the region-specific functional role of the RF was observed only in high-intensity contraction, such as >60% MVC. Although the participants and protocol were different, the results of this study showed a similar trend to that of the previous one. In contrast, the proximal region had a significantly higher HF/KE than the distal region in the injured RF. However, there was no significant difference between the proximal and middle regions (Figure 2a). There was a difference in the muscle activation pattern between the injured RF and the non-injured RF. This result means that the region-specific functional role was not uniform between the injured and non-injured RF.

The previous study on the BF found that the SEMG activity of eccentric contractions at 180 deg/s in the BF with strain injury was lower than that of the contralateral non-injured BF. Reductions in muscle activation during eccentric contraction are due to reduced motor unit recruitment and/or firing rates, which influence the maximal torque generation capabilities (Opar et al., 2013). The prior study suggested that reductions in hamstring activation may indicate that the previously injured BF was unable to withstand the same amount of stress before failure compared with the non-injured muscle (Opar et al., 2012, 2013). Concerning the effect of strain injury, it may not be necessary to consider the region of injury for the BF (Watanabe et al., 2016a). On the other hand, it may be necessary to consider the region of strain injury for the RF. In this study, RF strain injury occurred almost across from the proximal to the middle region. Therefore, the proximal region, not all regions, might be affected by strain injury.

In the comparison of the HF/KE in each channel, Ch 1 of the injured RF showed a significantly lower value than that of the non-injured RF (Figure 3). However, there was no significant difference between the injured Ch and the non-injured Ch. Therefore, the muscle activation of injured regions was not inhibited. It is not clear why only the HF/KE of Ch 1 was reduced. However, the reason might be related to the effect of the region-specific functional role of the RF. In five RF strain injuries in this study, the pseudocyst was seen in the proximal region. The injured regions might have been incompletely healed. Thus, the proximal regions of the RF may not be able to tolerate high contraction intensities. Watanabe et al. (2012) found that at high contraction intensities, central locus activations were located at the proximal region during hip flexion compared with those at low contraction intensities. Possibly, the most proximal and anterior surface of the muscle (Ch 1) might be regulated to reduce tension in the whole RF.

Concerning rehabilitation of RF strain injury, there are no established consensus guidelines or criteria for a safe return to sport after a muscle strain injury (Kary, 2010; Orchard et al., 2005).

As one prevention strategy for RF strain injury, Mendiguchia et al. (2013) recommended a greater use of concentric hip flexor strengthening exercises during the preseason. In our study, during hip flexion, muscle activation of the most proximal region in the injured RF was significantly lower than that of the non-injured RF. These results therefore support the prevention strategy of Mendiguchia et al. (2013) and suggest that rehabilitation should consider the function of the hip joint in proximal RF strain injuries. However, we could not clarify the relationship between the disorder of the region-specific functional role and the performance of the RF, and between the disorder and the risk for recurrent injury. Therefore, further studies are needed. The results of this study are likely to serve as fundamental information for obtaining new findings about rehabilitation of RF strain injuries.

Limitations

This study has several limitations. First, we were only able to assess injuries using low-field MRI. Although low-field MRI (0.3T) has been successfully used in previous studies of hamstring strain injuries (Cohen et al., 2011), it may not guarantee accurate assessment. Therefore, further investigation using high-field MRI or dynamic ultrasonography is required to verify the results of the current study. Second, the number of participants was small. In addition, the location of injury was not the same in all participants. It is difficult to collect participants with a history of only unilateral RF strain injury. However, other strain injuries had no effect on the results of this study. Although the location of injury was different, all participants were injured above the proximal half of the longitudinal line of the RF. Therefore, RF strain injury might affect the region-specific functional role of the muscle. To clarify the effects of RF strain injury, further investigation for each location of injury is required. Third, this study was a retrospective study. A study on the validity of self-reported retrospective injury data showed that if only the injury status (injured or not injured) was being associated with the outcome measure, the findings were likely to be very

accurate. However, requesting for further details would result in the reduction of the validity of the information provided (Gabbe et al., 2003). Thus, it was difficult to obtain the detail of injury, i.e., rehabilitation protocol, occurrence during a match or practice, time point during the match, and position on the field. Future prospective studies may help elucidate these mechanisms and their relationship with RF injuries. However, we did observe RF strain injury affecting the SEMG signal, therefore we believe this study provides novel findings that may aid the rehabilitation of RF strain injuries.

Conclusion

This is the first study on RF strain injury considering the region-specific activation properties of the RF. We investigated whether RF strain injury affected the region-specific functional role of the muscle. We found that the region-specific functional role was disturbed in the injured RF. In addition, the muscle activation of the most proximal parts was inhibited. Although further studies are needed to clarify the effect of RF strain injury on the region-specific functional role, we can conclude that RF strain injury partly affects muscle activation.

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