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Effect of change in patellofemoral joint contact area by the decrease in vastus medialis muscle activation on joint stress

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Purpose: Patellofemoral pain syndrome is a common orthopedic trauma among runners. It is unclear whether patellofemoral joint stress (PFJS) is the highest (or lowest) when the knee joint flexion angle and extension moment are in combination under the condition that vastus medialis (VM) activation decreases. This study aimed to investigate the effects of changes in the PFJ contact area by decreasing the activation of the VM muscle on PFJS. *Methods*: A PFJ sagittal model was used to quantify PFJ reaction force and PFJS. The PFJ model and mathematical modelling procedure were used to quantify PFJS based on previous studies. The simulation ranges were set to knee joint flexion angles of 10–45° and extension moments of 0–240 Nm. PFJS was calculated for the normal condition (NC) and decrease condition (DC) in VM activation. *Results*: When the knee joint angle and knee joint moment were at the maximum, the PFJS showed the maximum value under both conditions (NC; 14.9 N/cm^2, DC; 16.4 N/cm^2). PFJS was found to be higher in DC than that in NC for all simulation ranges. *Conclusion*: Decreased VM activation may be involved in the mechanism of patellofemoral pain syndrome. In addition, the results of this study provide evidence that clinicians can enhance VM to relieve pain in patients with patellofemoral pain syndrome.

Key words: *patellofemoral joint stress, vastus medialis, contact area, running*

1. Introduction

Running is a popular activity that many people can easily perform. Running activity has many beneficial effects, such as reducing the mortality rate of cardiovascular diseases [16]. However, running injuries are also likely to occur. Patellofemoral pain syndrome (PFPS) is a common orthopedic trauma among runners [26]. The occurrence of PFPS may precede the onset of patellofemoral osteoarthritis [7], [27]. One possible mechanism of PFPS is elevated patellofemoral joint (PFJ) stress (PFJS). Many previous studies have reported that individuals with PFPS exhibit greater PFJ stress when compared to pain-free controls during walking [15], stair descent [30] and squatting [10] using a mathematical model or finite element analysis. For example, PFJS during walking is significantly higher in individuals with PFPS (6.61 MPa) than that in controls (3.13 MPa) [15]. It is expected that the PFJS will increase further by repeating the movement. Given the relationship between PFJS and the occurrence mechanism of PFPS, decreasing PFJS may prevent the occurrence of PFPS and alleviate its symptoms.

Although there are many factors which may cause PFJS increase, a previous study [12] reported that lateral patellar maltracking is the most commonly cited reason. Lateral patellar maltracking is theorized to decrease PFJ contact area and increase PFJS, resulting in pain. Thus, patellar taping is performed to improve patellar maltracking, and the taping effect is useful for

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pain relief [1]. Patellar maltracking is caused by several factors, such as PF ligament properties [2], foot alignment [9], and altered muscle activation at the hip [6] and knee joint [3]. Among these, altered vastus medialis (VM) activation has attracted attention from clinicians. It is thought that VM activation pulls the patella in the medial direction and protects against lateral patellar maltracking. Some studies [18], [20] have reported that patellar maltracking is related to delayed VM activation compared to vastus lateralis activation. A cadaver study [8] has found that a decrease in VM activation caused a decrease in the PFJ contact area. Theoretical evidence has shown through computational studies that clinician interventions target VM in patients with PFPS [19]. Considering these facts, it is assumed that a decrease in VM activation causes the PFJ contact area to decrease, resulting in an increase in PFJS.

However, the effect of changes in the PFJ contact area due to a decrease in VM muscle activation on PFJS is unclear. Sawatsky et al. [23] showed that PFJS did not change before and after elimination of VM, but they used an animal (rabbit) knee model. The PFJ anatomy, such as the PF groove, differs between humans and rabbits [22]. Moreover, the authors of study [23] investigated PFJS under knee joint load and angle conditions, but did not consider the conditions of running. Because PFJS cannot be directly measured in vivo, PFJS can be estimated based on the knee joint moment and angle using a mathematical model. Given that PFPS is likely to occur in running, it is necessary to calculate PFJS considering knee joint kinetics and kinematics during running, which has not been revealed. Moreover, because the knee joint angle and moment exhibit various combinations during the stance phase of running, PFJS also fluctuates during the stance phase. Under the condition that VM activation decreases, it is unclear whether PFJS is the highest (or lowest) when the knee joint flexion angle and extension moment are in combination. A recent study [28] investigated the influence of knee joint angle and extension moment on PFJS, but did not consider VM muscle activation decrease. Additionally, the effect of sex and knee joint rotation on patellofemoral joint stress has been reported using a mathematical model [25], but the influence of VM muscle activation on PFJS is still unclear.

Therefore, this study aimed to investigate the effect of changes in the PFJ contact area on PFJS by decreasing VM muscle activation. Since decreased VM muscle activation decreases the PFJ contact area [8], we hypothesized that PFJS increases when VM muscle activation decreases compared to its normal condition.

2. Materials and methods

2.1. Modelling setting

The PFJ model and mathematical modelling procedure were used to quantify PFJS based on previous studies [5], [15]. The input variables required were the knee joint flexion angle and extension moment. Before the calculation of PFJS, the simulation range of the knee joint extension moment and flexion angle must be determined under running conditions because PFPS is likely to occur during running. The present study used the simulation ranges used in a previous study [28]. A previous study [28] calculated based on dataset (http://pesquisa.ufabc.edu.br/bmclab/datasets/rbds/) of running in Fukuchi's study [11]. From a public data set (total average of 28 individuals), the lower and upper limit of knee joint flexion angle and extension moment during stance phase of 2.5, 3.5, and 4.5 m/s were calculated so that the results of this study could be applied to various running speeds. The lower and upper limits of the knee joint flexion angle were 12–44°, respectively, and those of the knee joint extension moment were −51 Nm to 235 Nm during the stance phase, respectively. Therefore, the simulation ranges in this study were set as follows: knee joint angle, 10–45° and knee extension moment, 0–240 Nm. Given that the negative value (−51 Nm) of the knee joint moment indicates the knee joint flexion moment, the lower limit value was 0 Nm. The step sizes of the knee joint flexion angle and extension moment were

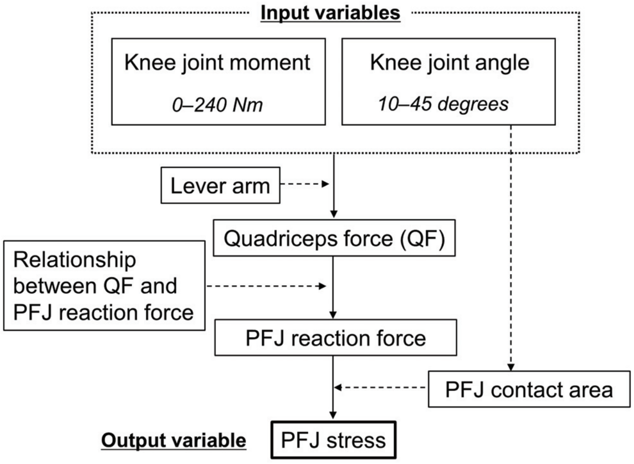

Fig. 1. Procedure of patellofemoral joint (PFJ) kinetic calculation. All combinations of knee joint flexion angle and extension moment (i.e., 17,352 times = 36 (10–45°) angles × 241 (0–240 Nm) moments × 2 conditions) were calculated under the normal condition and decreased condition in vastus medialis activation

one degree and one Newton meter, respectively. All combinations of knee joint flexion angle and extension moment (i.e., 17,352 times = 36 (10–45°) angles × 241 (0–240 Nm) moments × 2 conditions) were calculated under the normal condition (NC) and decreased condition (DC) in VM activation (Fig. 1). Because this study was a mathematical study, obtaining informed consent was not required.

2.2. PFJ contact area calculation by VM activation change

To compute the PFJS in the NC and DC in the abovementioned simulation ranges of the knee joint angle, this study calculated the PFJ contact area based on the data of Csintalan et al. [8]. The present study utilized the PFJ contact area of NC and DC, all knee joint flexion angles (0, 30, 60 and 90°), and neutral tibial rotation in males in a previous study [8]. In the NC group, muscle loading was performed under standard conditions (loading condition of 100%; vastus medialis, 67 N; vastus intermedius/rectus femoris, 111 N; vastus lateralis, 98 N; iliotibial band, 27 N). This condition was based on the cross-sectional muscle area [32]. DC represents only VM activation decreased to 33.5 N.

The equations of the PFJ contact area were calculated by third-order polynomial curve fitting to the contact areas in knee flexion angles (0, 30, 60 and 90°) for NC and DC continuous contact areas in the simulation range of the knee flexion angle. All polynomial curves passed all measured contact areas obtained in a previous study [8] and had a fairly good fit. Using these polynomial equations, the PFJ contact area, which is specific to the VM activation conditions, was calculated in the simulation range of the knee joint angle (10–45°).

2.3. PFJ kinetic calculation

The PFJS was calculated using a previously reported method [28]. First, the quadriceps effective lever arm was determined at each knee flexion angle by fitting a nonlinear equation to the data [31]. Second, the quadriceps force was calculated by dividing the knee extension moment by the calculated effective lever arm force. Third, the PFJ reaction force was estimated by multiplying the quadriceps force by a constant [29], which defines the relationship between the PFJ reaction force and the knee joint flexion angle [5], [29], [31]. Finally, the PFJS was calculated by dividing the PFJ reaction force by the PFJ contact area for NC and DC. The above-mentioned steps were performed, and our study examined the effect of changes in the PFJ contact area by decreasing VM muscle activation on PFJ joint stress. All calculations were performed using custom-written MATLAB code (R2019a; MathWorks, Inc., Natick, MA, USA).

3. Results

Under both conditions, the PFJ reaction force increased as the knee flexion angle and extension moment increased. PFJS increased as the knee extension moment increased. Hence, the PFJS decreases when the extension moment decreases. However, the relationship between the PFJS and knee joint flexion angle differed from the relationship between the PFJ reaction force and knee joint extension moment. Regardless of NC and DC, the PFJS was at the minimum when the knee joint was 16° among all knee joint extension moment values. Furthermore, the PFJS was the maximum when the knee joint was 45 degrees among all knee joint extension moment values in both conditions. When the knee joint angle and knee joint moment were at the maximum, the PFJS showed the maximum value under both conditions (NC; 14.9 N/cm^2, DC; 16.4 N/cm^2). For all combinations of knee joint angles and knee joint moments, the PFJS in DC was higher than that in NC (Fig. 2). For example, when the knee joint moment was at the maximum (240 Nm), the PFJS in DC was higher than that in NC at all knee joint angles (10–45°) (Fig. 3).

4. Discussion

This study aimed to investigate the effect of changes in the PFJ contact area by decreasing VM muscle activation on PFJS. The strength of this study is that PFJS was calculated under NC and DC through a mathematical model considering the kinetic data [11] during running. A change in VM activation is thought to cause lateral patellar maltracking [18], [20]. Consequently, this maltracking seems to increase the PFJS, which is involved in the development of PFPS, but this has not been clarified so far. Furthermore, the amplitude of the PFJS changes depending on the change in each knee joint angle and moment [28]. However, it remains unclear which combinations of the knee joint flexion angle and extension moment

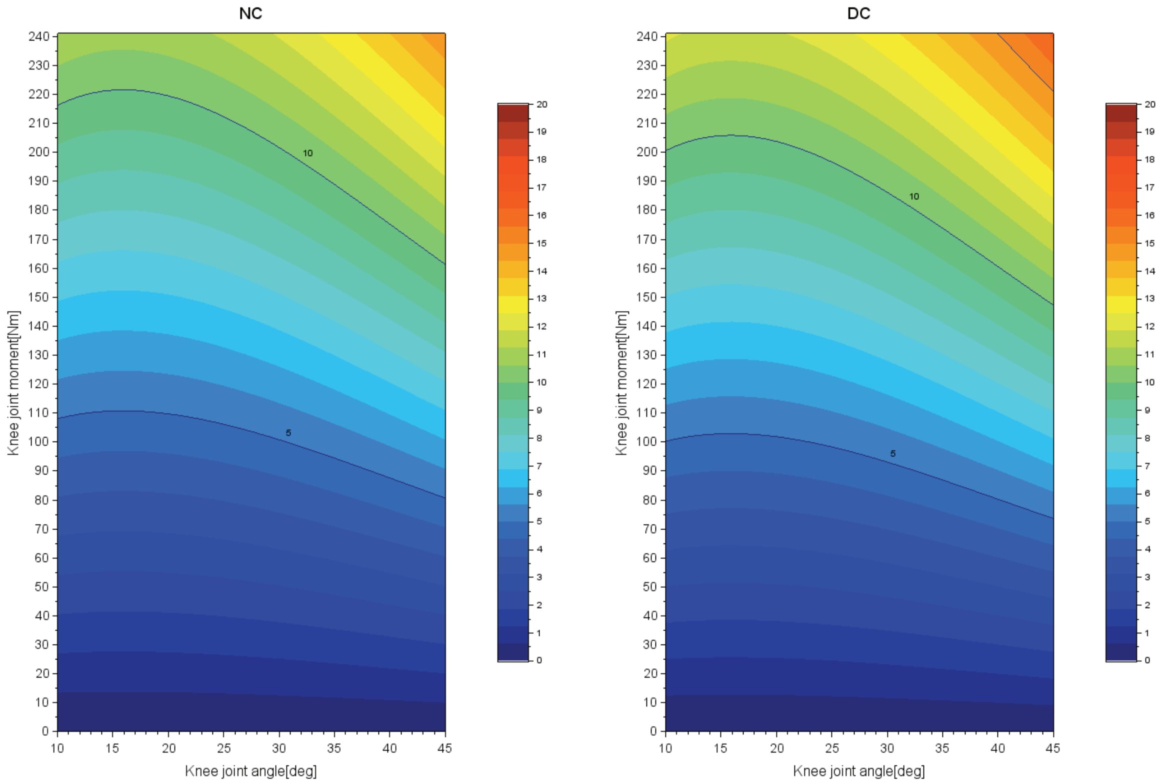

Fig. 2. Contour lines of patellofemoral joint stress on a two-dimensional plot of knee joint extension moment and flexion angle in normal condition (NC) and decrease condition (DC) in vastus medialis activation

result in the highest (or lowest) PFJS when VM activation changes. To the best of our knowledge, the present study is the first to demonstrate the influence of changes in the PFJ contact area by a decrease in VM muscle activation on PFJS at various knee joint flexion angles and extension moments. These findings provide evidence that a decrease in VM activation may be involved in the mechanism of PFPS.

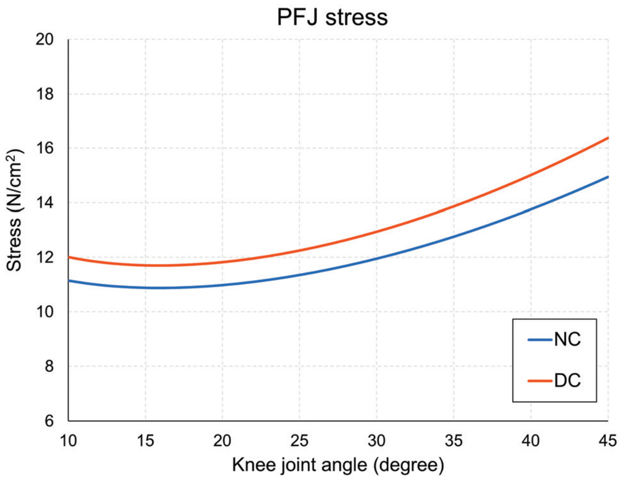

Fig. 3. Patellofemoral joint (PFJ) stress against knee flexion angle at a constant of 240 Nm in knee joint moment in knee joint moment in normal condition (NC) and decreased condition (DC) of vastus medialis

The results of the present study supported our hypothesis that PFJS in DC was higher than that in NC for all combinations of knee joint angles and knee joint moments. It has been reported that PFJS does not change when VM activation decreases [23], but recent studies have shown that PFJS increases when VM activation decreases [13], as in the present study. These studies targeted a rabbit model, but the present study was able to demonstrate it for a human cadaver. Moreover, assuming running conditions, this study newly investigated PFJS for various combinations of knee joint flexion angles and moments. PFJS in DC was higher than that in NC, which was believed to be caused by the differences in the contact area between NC and DC. The PFJ contact area in this study was calculated by a third-order polynomial curve fitting to the contact areas in various knee flexion angles for NC and DC in a previous study [8], and the simulation range of the knee joint angle (10–45°) was utilized based on running data [11]. According to the calculated PFJ contact area (Fig. 4), DC showed low values for all knee joint angles compared with NC. Decreased PFJ contact area increases PFJS [13], [28]. Furthermore, a previous study [21] also reported that increasing the PFJ contact area with a knee brace reduces PFJS and consequently reduces pain in patients with PFPS. Thus, the observed PFJS between NC and

DC in the present study was likely due to the difference in the PFJ contact area.

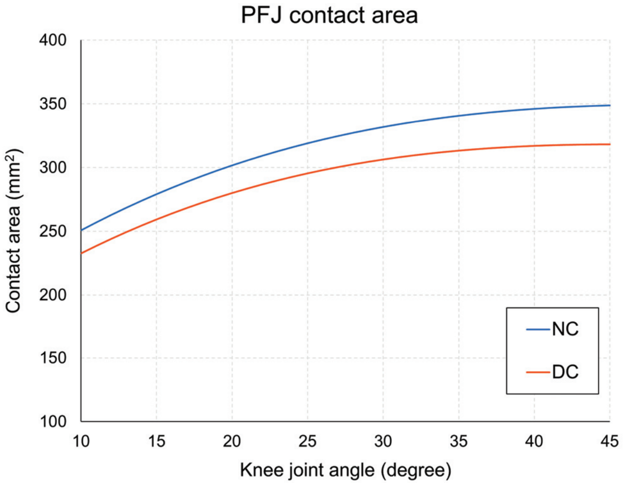

Fig. 4. Patellofemoral joint (PFJ) contact area against knee flexion angle in normal condition (NC) and decreased condition (DC) of vastus medialis activation

Among all knee joint extension moment values in both conditions, the PFJS had the minimum and maximum values when the knee joint was 16 and 45°, respectively. The PFJ reaction force is likely to increase as the knee joint flexion angle and extension moment increase [4], [5], which is consistent with the findings of the present study. Since the simulation range was 10 to 45°, the minimum and maximum values of PFJS appeared at knee joint angles of 10 and 45°, but the minimum value of PFJS was at 16° and not 10°. The main reason for this result can be explained by the relationship between the PFJ reaction force and PFJ contact area based on a previous study [28]. Because the PFJS was obtained by dividing the PFJ reaction force by the PFJ contact area, the PFJS was influenced by both factors. Hence, the PFJS is at its lowest when the PFJ reaction force is low and the PFJ contact area is large. For example, while the PFJ reaction force continued to increase as the knee flexion angle increased, the contact area continued to increase as the knee flexion angle increased. When the knee joint flexion angle is at its minimum value (10°), both the PFJ reaction force and contact area also show minimum values. Therefore, although the PFJ reaction force is at its lowest when the knee joint flexion angle (10°) is at its minimum value, the contact area is also at its lowest; thus, the PFJS is not necessarily at its lowest when the knee joint flexion angle is at its minimum value (10°). The PFJS is determined by the relationship between the PFJ reaction force and the PFJ contact area, and it is considered that PFJS is at its lowest or highest at a specific knee joint flexion angle, such as 16 or 45°, respectively.

Our findings may be beneficial in reducing and preventing symptoms in patients with PFPS. In previous studies [10], [15], [30], individuals with PFPS exhibited greater PFJS when compared to pain-free controls in various tasks. One of the reasons for these results is believed to be the decrease in PFJ contact area. Powers et al. [21] showed that wearing a knee brace when walking reduces pain in patients with PFP immediately due to decreased PFJS. Therefore, it is important to increase the PFJ contact area to alleviate PFPS symptoms. In this study, because PFJS increased in the DC of the VM, strengthening the VM for runners with symptoms of PFPS may increase the PFJ contact area and consequently decrease pain. Furthermore, the PFJS was the lowest at 16° in both conditions. Thus, if patients with PFPS have decreased VM activation, it may help reduce pain to slightly flex the knee (app. 16°) during the running stance phase.

The present study has some limitations. The PFJ model used to estimate the PFJS was a simplified planar model, thus, this model does not consider the individual three-dimensional patella. Patellar kinematics during a loading task differ between patients with and without PFPS [33]. Moreover, recent study [24] found that adolescents and adults with PFPS exhibit distinct patellar tracking. Individual alterations in patellar kinematics may also affect the contact area, thereby affecting the PFJS. In addition, this study calculated specific PFJ contact areas, such as ND and DC, but the contact area was based on cadaver data [8]. Therefore, they may differ from the contact area *in vivo*. Furthermore, because PFJS cannot be directly measured *in vivo*, a systematic review [17] has also reported that many studies use the contact area of cadaver data, as in the present study. Finally, this study determined the simulation range of the knee flexion angle assuming running condition. A recent meta-analysis [14] reported that PFJ reaction force was high for larger knee flexion movements such as squatting. Therefore, the results may not be generalizable to such movements. These limitations should be addressed in future research.

5. Conclusions

The PFJS in DC was higher than that in NC for all combinations of knee joint angles and knee joint moments. As one possible occurrence mechanism of PFPS is elevated PFJS, these findings provide evidence that a decrease in VM activation may be involved in the occurrence mechanism of PFPS. In addition, the results of this study provide evidence that clinicians can enhance VM to relieve pain in patients with PFPS.

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References

[1] AMINAKA N., GRIBBLE P.A., *Patellar taping, patellofemoral pain syndrome, lower extremity kinematics, and dynamic postural control*, J. Athl. Train., 2008, 43 (1), 21–28, DOI: 10.4085/1062-6050-43.1.21.

[2] AMIS A.A., FIRER P., MOUNTNEY J., SENAVONGSE W., THOMAS N.P., *Anatomy and biomechanics of the medial patellofemoral ligament*, Knee, 2003, 10 (3), 215–220, DOI: 10.1016/s0968-0160(03)00006-1.

[3] BESIER T.F., FREDERICSON M., GOLD G.E., BEAUPRE G.S., DELP S.L., *Knee muscle forces during walking and running in patellofemoral pain patients and pain-free controls*, J. Biomech., 2009, 42 (7), 898–905, DOI: 10.1016/j.jbiomech.2009.01.032.

[4] BONACCI J., HALL M., FOX A., SAUNDERS N., SHIPSIDES T., VICENZINO B., *The influence of cadence and shoes on patellofemoral joint kinetics in runners with patellofemoral pain*, Journal of Science and Medicine in Sport, 2018, 21 (6), 574–578, DOI: 10.1016/j.jsams.2017.09.593.

[5] BONACCI J., VICENZINO B., SPRATFORD W., COLLINS P., *Take your shoes off to reduce patellofemoral joint stress during running*, Br. J. Sports Med., 2014, 48 (6), 425–428, DOI: 10.1136/bjsports-2013-092160.

[6] COWAN S.M., CROSSLEY K.M., BENNELL K.L., *Altered hip and trunk muscle function in individuals with patellofemoral pain*, Br. J. Sports Med., 2009, 43 (8), 584–588, DOI: 10.1136/bjsm.2008.053553.

[7] CROSSLEY K.M., *Is patellofemoral osteoarthritis a common sequela of patellofemoral pain?*, Br. J. Sports Med., 2014, 48 (6), 409–410, 10.1136/bjsports-2014-093445.

[8] CSINTALAN R.P., SCHULZ M.M., WOO J., MCMAHON P.J., LEE T.Q., *Gender differences in patellofemoral joint biomechanics*, Clin. Orthop. Relat. Res., 2002 (402), 260–269.

[9] DUFFEY M.J., MARTIN D.F., CANNON D.W., CRAVEN T., MESSIER S.P., *Etiologic factors associated with anterior knee pain in distance runners*, Med. Sci. Sports Exerc., 2000, 32 (11), 1825–1832, DOI: 10.1097/00005768-200011000-00003.

[10] FARROKHI S., KEYAK J.H., POWERS C.M., *Individuals with patellofemoral pain exhibit greater patellofemoral joint stress: a finite element analysis study*, Osteoarthritis Cartilage, 2011, 19 (3), 287–294, 10.1016/j.joca.2010.12.001.

[11] FUKUCHI R.K., FUKUCHI C.A., DUARTE M., *A public dataset of running biomechanics and the effects of running speed on lower extremity kinematics and kinetics*, Peer J., 2017, 5, e3298, 10.7717/peerj.3298.

[12] FULKERSON J.P., *Diagnosis and treatment of patients with patellofemoral pain*, Am. J. Sports Med., 2002, 30 (3), 447–456, DOI: 10.1177/03635465020300032501.

[13] HAN S.W., SAWATSKY A., JINHA A., HERZOG W., *Effect of vastus medialis loss on rabbit patellofemoral joint contact pressure distribution*, Journal of Applied Biomechanics, 2020, 36 (6), 390–396, DOI: 10.1123/jab.2020-0056.

[14] HART H.F., PATTERSON B.E., CROSSLEY K.M., CULVENOR A.G., KHAN M.C.M., KING M.G. et al., *May the force be with you: understanding how patellofemoral joint reaction force compares across different activities and physical interventions – a systematic review and meta-analysis*, Br. J. Sports Med., 2022, DOI: 10.1136/bjsports-2021-104686.

[15] HEINO BRECHTER J., POWERS C.M., *Patellofemoral stress during walking in persons with and without patellofemoral pain*, Med. Sci. Sports Exerc., 2002, 34 (10), 1582–1593, DOI: 10.1249/01.MSS.0000035990.28354.c6.

[16] LEE D.C., PATE R.R., LAVIE C.J., SUI X., CHURCH T.S., BLAIR S.N., *Leisure-time running reduces all-cause and cardiovascular mortality risk*, J. Am. Coll. Cardiol., 2014, 64 (5), 472–481, DOI: 10.1016/j.jacc.2014.04.058.

[17] NUNES G.S., SCATTONE SILVA R., DOS SANTOS A.F., FERNANDES R.A.S., SERRÃO F.V., DE NORONHA M., *Methods to assess patellofemoral joint stress: A systematic review*, Gait and Posture, 2018, 61, 188–196, DOI: 10.1016/j.gaitpost.2017.12.018.

[18] PAL S., BESIER T.F., DRAPER C.E., FREDERICSON M., GOLD G.E., BEAUPRE G.S. et al., *Patellar tilt correlates with vastus lateralis: vastus medialis activation ratio in maltracking patellofemoral pain patients*, J. Orthop. Res., 2012, 30 (6), 927–933, DOI: 10.1002/jor.22008.

[19] PAL S., BESIER T.F., GOLD G.E., FREDERICSON M., DELP S.L., BEAUPRE G.S., *Patellofemoral cartilage stresses are most sensitive to variations in vastus medialis muscle forces*, Comput. Methods Biomech. Biomed. Engin., 2019, 22 (2), 206–216, DOI: 10.1080/10255842.2018.1544629.

[20] PAL S., DRAPER C.E., FREDERICSON M., GOLD G.E., DELP S.L., BEAUPRE G.S. et al., *Patellar maltracking correlates with vastus medialis activation delay in patellofemoral pain patients*, Am. J. Sports Med., 2011, 39 (3), 590–598, DOI: 10.1177/0363546510384233.

[21] POWERS C.M., WARD S.R., CHEN Y.J., CHAN L.D., TERK M.R., *The effect of bracing on patellofemoral joint stress during free and fast walking*, Am. J. Sports Med., 2004, 32 (1), 224–231.

[22] RUDERT M., *Histological evaluation of osteochondral defects: consideration of animal models with emphasis on the rabbit, experimental setup, follow-up and applied methods*, Cells Tissues Organs, 2002, 171 (4), 229–240, DOI: 10.1159/000063125.

[23] SAWATSKY A., BOURNE D., HORISBERGER M., JINHA A., HERZOG W., *Changes in patellofemoral joint contact pressures caused by vastus medialis muscle weakness*, Clinical Biomechanics, 2012, 27 (6), 595–601, https://doi.org/10.1016/j.clinbiomech.2011.12.011

[24] SHEN A., BODEN B.P., GRANT C., CARLSON V.R., ALTER K.E., SHEEHAN F.T., *Adolescents and adults with patellofemoral pain exhibit distinct patellar maltracking patterns*, Clinical Biomechanics, 2021, 90, DOI: 10.1016/j.clinbiomech.2021.105481.

[25] TAKABAYASHI T., EDAMA M., INAI T., TOKUNAGA Y., KUBO M., *Influence of sex and knee joint rotation on patellofemoral joint stress*, Acta Bioeng. Biomech., 2022, 24 (3), 161–168, 10.37190/ABB-02115-2022-03.

[26] TAUNTON J.E., RYAN M.B., CLEMENT D.B., MCKENZIE D.C., LLOYD-SMITH D.R., ZUMBO B.D., *A retrospective case-control analysis of 2002 running injuries*, Br. J. Sports Med., 2002, 36 (2), 95–101

[27] THOMAS M.J., WOOD L., SELFE J., PEAT G., *Anterior knee pain in younger adults as a precursor to subsequent patellofemoral osteoarthritis: a systematic review*, BMC Mus-

culoskelet. Disord., 2010, 11, 201, DOI: 10.1186/1471-2474-11-201.

[28] TOMOYA T., MUTSUAKI E., TAKUMA I., YUTA T., MASAYOSHI K., *A mathematical modelling study investigating the influence of knee joint flexion angle and extension moment on patellofemoral joint reaction force and stress*, Knee, 2019, 26 (6), 1323–1329, DOI: 10.1016/j.knee.2019.10.010.

[29] VAN EIJDEN T.M., KOUWENHOVEN E., VERBURG J., WEIJS W.A., *A mathematical model of the patellofemoral joint*, J. Biomech., 1986, 19 (3), 219–229

[30] WAITEMAN M.C., BRIANI R.V., PAZZINATTO M.F., FERREIRA A.S., FERRARI D., DE OLIVEIRA SILVA D. et al., *Relationship between knee abduction moment with patellofemoral joint reaction force, stress and self-reported pain during stair descent in women with patellofemoral pain*, Clin. Biomech. (Bristol, Avon), 2018, 59, 110–116, DOI: 10.1016/j.clinbiomech.2018.09.012.

[31] WHYTE E.F., MORAN K., SHORTT C.P., MARSHALL B., *The influence of reduced hamstring length on patellofemoral joint stress during squatting in healthy male adults*, Gait and Posture, 2010, 31 (1), 47–51, https://doi.org/10.1016/j.gaitpost.2009.08.243

[32] WICKIEWICZ T.L., ROY R.R., POWELL P.L., EDGERTON V.R., *Muscle architecture of the human lower limb*, Clin. Orthop. Relat. Res., 1983 (179), 275–283.

[33] WILSON N.A., PRESS J.M., KOH J.L., HENDRIX R.W., ZHANG L.Q., *In vivo noninvasive evaluation of abnormal patellar tracking during squatting in patients with patellofemoral pain*, J. Bone Joint Surg. Am., 2009, 91 (3), 558–566, DOI: 10.2106/jbjs.g.00572.