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Impact of Structural and Physiological Changes in the Vastus Medialis Muscle Following Anterior Cruciate Ligament Injury and Reconstruction on Short Term Patient-Reported Knee Function

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SUMMARY

Objective. The objective of this study was to observe the structural and physiological changes in vastus medialis and its impact on short-term patient-reported knee function following anterior cruciate ligament (ACL) injury and reconstruction.

Patients and methods. A prospective observational study was conducted on 16 young individuals with an ACL injury. The cross-sectional area (CSA) of vastus medialis was measured using ultrasonography. Surface electromyography of vastus medialis (VM) was assessed during maximum voluntary isometric contraction (MVIC). These parameters were assessed preoperatively and six months postoperatively along with the International knee documentation committee (IKDC) 2000 score. The unaffected limb was used as control. Following ACL reconstruction surgery, all individuals underwent standard rehabilitation protocol. ANOVA with *post hoc* analysis was used to determine the difference in CSA and MVIC between the injured and unaffected sides.

Results. When compared to the unaffected side, we found that the CSA of the VM decreased by 13.39% following injury and subsequently decreased by 41.05% at the end of 6 months post ACL reconstruction ($p = 0.001$). Similarly, after injury, the MVIC of VM was lowered by 12.05%, and after six months of ACL reconstruction, it was reduced by another 23.15% ($p = 0.075$). On the contrary, the subjective knee function score improved considerably after six months following surgery ($p = 0.001$).

Conclusions. To conclude, our study observed an inverse relationship in patient-reported functional outcome measures and structural and physiological morphology of VM in individuals who have undergone ACLR.

KEY WORDS

IKDC; quadriceps muscle; electromyography; ACL injury; reconstruction.

INTRODUCTION

Recovery following anterior cruciate ligament (ACL) injury and reconstruction largely depends on the extensor mechanism. In particular, the quadriceps play a vital role in restoring the functional status of any individual. It has been observed that there can be up to a 40 % deficit of quadriceps strength following ACL injury, reconstruction, and rehabilitation (1). Palmieri *et al.* (2) have reported that more than 20% of quadriceps muscle strength deficit was present at the end of six months following ACL reconstruction. Quadriceps atrophy is a common observation following ACL injury and rehabilitation and is always associated with weakness. Vastus medialis (VM), which has an essential role in knee extension, is subjected to structural and physiological changes owing to its complex architecture and innervations (3). It regulates and pulls the longitudinal fibres of the quadriceps muscle medially and dorsally due to the horizontal orientation of the muscle fibres and creates a pre-strain during terminal extension (4). In the absence of this mechanism, the longitudinal fibres would be slack and weak to produce an effective extension torque at the knee joint. This regulative function of VM is imperative, and hence atrophy of VM precedes more rapidly than the other components immediately following inactivity (5). "Regional activation" of VM is facilitated by limited region motor neuron innervations, which regulate the activation strategies during complex knee functions. Also, structurally VM offers a predominant contribution medially into all layers of the quadriceps tendon and which makes it susceptible to atrophy following ACL injury (6, 7). In previous studies, the changes in knee extensor mechanism and the strength deficits were discussed as a gross entity, but the impact of structural and morphological changes in VM on patients' reported knee function has not been studied. This study focuses on the impact of structural and physiological changes of VM on patient-reported outcome measures in individuals with an ACL injury and following reconstruction.

PATIENTS AND METHODS

This prospective observational study was conducted between January 2018 and July 2019 at our tertiary care hospital after obtaining approval from the institutional ethical committee (JIPMER - Date of acceptance 11/08/2017, Protocol no. JIP/IEC/2017/0321). All patients between 18 and 40 years who presented with knee instability secondary to an ACL injury within 3 to 6 months from the injury time were included. Patients with avulsion fractures, prior knee infection or surgery, associated posterior cruciate ligament or grade II/III collateral ligament injury, associated meniscal injuries, and radiograph suggestive of greater than grade I Kellegren-Lawrence arthritis were excluded from this study. Functional outcome using subjective IKDC 2000 Score was calculated preoperatively and 6-months postoperatively. Cross-sectional area (CSA) and maximum voluntary isometric contraction (MVIC) of vastus medialis was assessed using ultrasonography and surface electromyography (EMG), respectively. These observations were made preoperatively and after six months following surgery. The measurements of the uninjured limb were used as the control. All the individuals selected for this study underwent uniform preoperative rehabilitation for 4-6 weeks. Patients were taken up for surgery after satisfying the prerequisites of achieving: 1) neutral extension and 2) 90% of quadriceps strength symmetry. ACL reconstruction surgery was done using either a bone-patellar tendon graft or hamstring graft by two experienced surgeons in a tertiary care centre. All the individuals underwent standard ACL rehabilitation protocol and were followed at 2, 4, 6 weeks, three months, and six months.

Assessment of maximum voluntary isometric contraction of the vastus medialis muscle using surface electromyography

Surface electrodes were placed along the longitudinal axes of VM as per the recommendations of surface electromyography for the non-invasive assessment of muscles (SENIAM project) (8). Electrodes were placed at 80% of the distance from the anterior superior iliac spine and the medial border of the patella. The muscle's distal aspect was palpated with the knee bent to 90 degrees of flexion, and the electrode was placed on the most prominent part. The reference electrodes were placed around the ankle joint of the other limb. The subject was asked to extend the leg when seated in a high sitting position. The EMG values were noted from three successive attempts with adequate rest periods. The best reading was noted as the maximum voluntary isometric contraction (MVIC), measured in microvolts using surface EMG (EP/EMG machine/MB 9200K/Nihon Khoden/Japan). The same procedure was repeated on the contralateral limb, which was taken as control.

Assessment of CSA of vastus medialis using ultrasonography

The cross-sectional area of the vastus medialis muscle was measured by the SIEMENS ACUSON S3000 ultrasound machine (Siemens, Erlangen, Germany) using a linear 61CD transducer (**figure 1**).

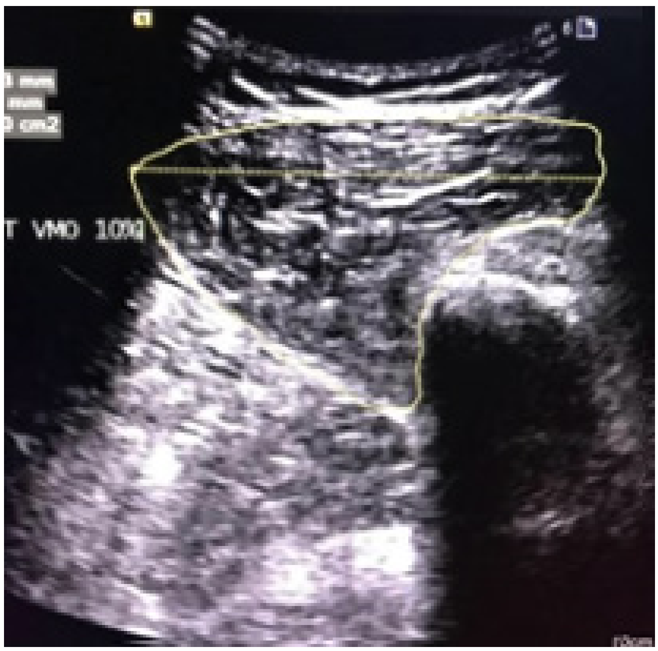

Figure 1. Ultrasonographic image showing measurement of CSA of vastus medialis.

A line from the central point of the patella to the medial aspect of the anterior superior iliac spine was marked to obtain the images. Axial perpendicular lines were then marked at 10, 30, and 50% intervals from this point. Measurements were done after the participant had rested in the horizontal position for 20 minutes to allow fluid shifts to stabilize. A consistent, minimal pressure was applied with the probe to the skin to avoid muscle compression, aided by the application of a transmission gel to improve acoustic coupling. The participants were instructed to relax their muscles. The measurements were done at 10%, 30%, and 50% levels. The average of the three values was noted. These were done by an experienced radiologist.

For the demographical and clinical outcomes, categorical data were expressed as percentages and numerical variables as mean and standard deviations. The paired t-test was used to compare IKDC scores of the affected limb after ACL injury and after six months following ACL reconstruction. ANOVA with *post hoc* was utilized to test the difference in CSA and MVIC between the injured and unaffected (control) sides. Spearman correlation coefficient was used to examine the relationship between CSA, MVIC, and IKDC scores of the injured side. IBM SPSS Statistics for Windows, Version 20.0, was used to analyze the data. IBM Corp., Armonk, New York. The statistical significance level was set at $p < 0.05$ (Two-tailed).

Ethics

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent was taken from all the included subjects.

RESULTS

Twenty-eight patients fulfilled the eligibility criteria, however, only 16 were included in the trial because four had a concomitant meniscal injury and one had grade 2 cartilage damage which was identified intra-operatively. Seven patients were lost owing to long-distance travel (**figure 2**).

Males predominated among the 16 participants in the study, and the right side was more involved than the left (**table I**). Twelve patients had their ACLs reconstructed using a bone-patellar tendon-bone graft, whereas four others had quadrupled hamstring grafts.

In comparison to the unaffected side, the CSA of VM decreased by 13.39% post ACL injury and subsequently decreased further to 41.05% at the end of 6 months following ACL surgery ($p = 0.001$). Similarly, after injury, the MVIC of VM decreased by 12.05%, and after six months of ACL reconstruction, it decreased further to 23.15% ($p = 0.075$) (**figures 3, 4**). On the contrary, after six months following ACL reconstruction, the subjective knee function score improved dramatically ($p = 0.001$) (**table II**). According to the findings, only CSA exhibited a moderate negative relationship with IKDC scores ($r = -0.588$; $p = 0.02$).

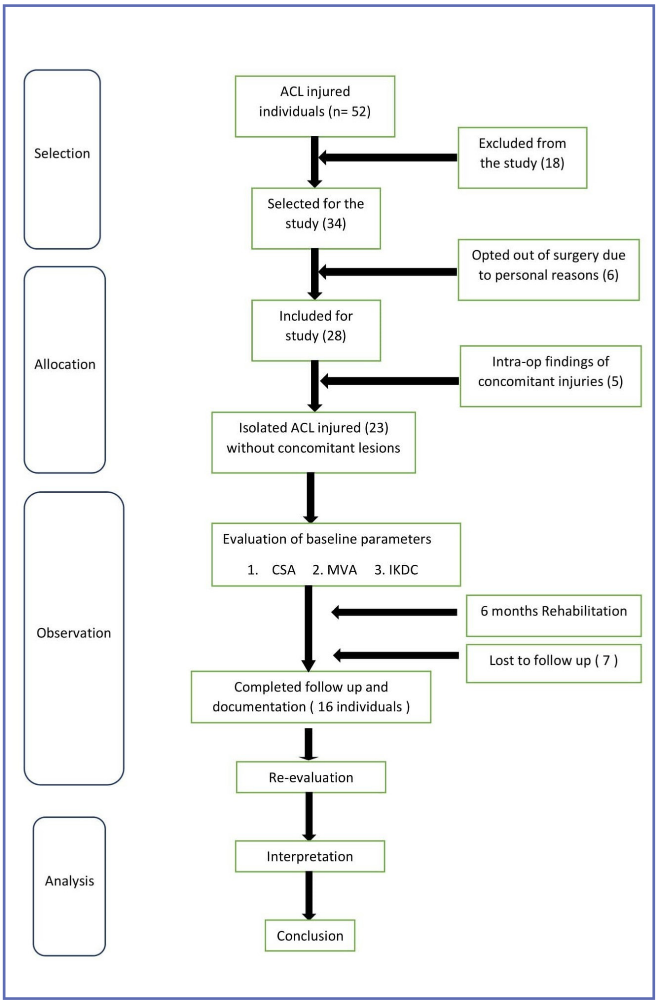

Figure 2. Flowchart showing the selection of study participants.

Table I. Demographic details.

Subject characteristics	Number of subjects	%
Gender		
Female	3	18.8
Male	13	81.3
Side of injury		
Left	6	37.5
Right	10	62.5

Table II. Mean comparison of CSA, MVIC of VM and IKDC scores.

Outcome measure	Unaffected limb (mean ± SD)	Affected limb after ACL injury (mean ± SD)	Difference (%)	Affected side after ACL injury rehabilitation (mean ± SD)	Difference (%)	P-value
CSA of VM (cm^2)	10.75 ± 3.34	9.31 ± 3.21	13.39	6.44 ± 2.50	41.05	< 0.001
MVIC/ EMG of VM (micro volts)	2773.87 ± 918.456	2440.06 ± 1446.168	12.05	2131.75 ± 1004.488	23.15	0.075
IKDC	Preop: 44.74 ± 8.72		Postop: 76.03 ± 14.69			< 0.001

CSA: cross sectional area; MVIC: maximum voluntary isometric contraction; VM: vastus medialis; EMG: electromyography; IKDC: International Knee Documentation Committee.

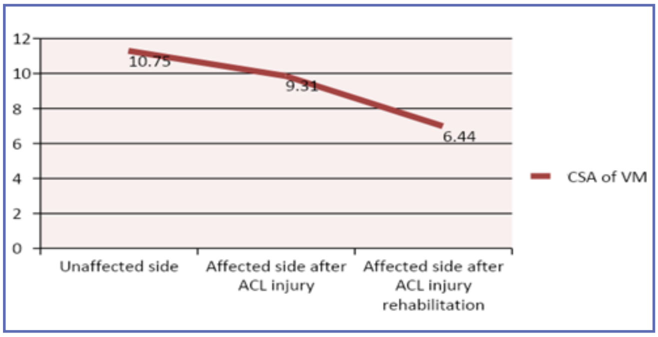

Figure 3. Image showing comparison of pre –post scores of CSA of VM with Unaffected side.

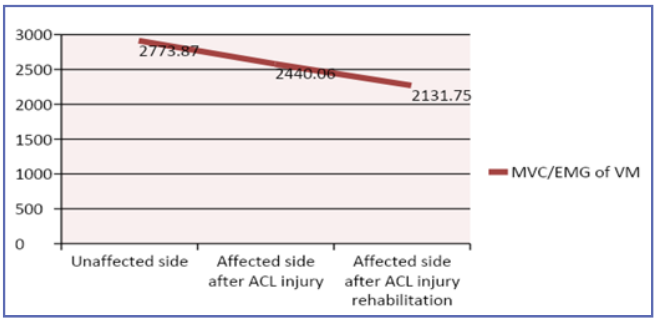

Figure 4. Image showing comparison of pre –post scores of MVC of VM with Unaffected side.

DISCUSSION

The present study observed VM structural and physiological morphology following an ACL injury and after six months of reconstruction and rehabilitation. The percentage reduction of CSA and MVIC of VM was calculated as 13.39 % and 12.05 %, respectively, and after six months of ACL reconstruction, it reduced further to 41.05 % and 23.15 %, respectively, compared to the unaffected side VM. However, there was a significant improvement in the patient-reported outcome score.

It has been observed that the CSA of VM has a significan impact on the successful outcome following ACLR (9). In ACL deficient knees, neuro-muscular impairment can lead to a reduction in CSA. Neurogenic muscular atrophy is characterized by the depletion in type-II fibres which is initiated by pain-mediated weakness (10). This phenomenon can be a trigger for VM atrophy following ACL injury. In this study, the reduction in MVIC of VM compared to the opposite side is a direct implication of reduced force production by the affected limb, which can be proportional to the size of the muscle. A study conducted by Williams *et al.* (11) also found results in line with the current study stating that these adaptations in muscle morphology varied with individuals, proportional to the physical demands placed after injury and following reconstruction. These adaptations lead to the clauses of copers and non-copers, consistent with the muscle volume and its strength quotient. The global atrophy of quadriceps muscle volume was noted to be 4.5 % to 13 % in non-copers compared to their opposite side. Even though there is no precise classification in identifying copers and non-copers, quadriceps weakness was consistent with its muscle volume. A systematic review which was conducted recently on quadriceps muscle size following ACL injury and reconstruction showed a slight reduction in quadriceps cross-sectional area following injury, which may be persistent despite regular rehabilitation program (12). However, the observations made by Chaves *et al.* (7) were in contrast to our findings. They observed that the neuromuscular efficie - cy of VMO was fully re-established following ACL reconstruction. The potential confounding factor could be the samples who were high-performance soccer athletes.

It has been observed that there has been a symmetric recruitment pattern of VM and VL to electrical and mechanical responses, which ensures loss of torque production in any one of the components in the quadriceps group may be equally attributed to the other (13). However, the collagen content of vastus lateralis remains unchanged despite prolonged bed rest and inactivity, which makes VM more vulnerable to morphological adaptations (14). Eventually, it was observed that the motor unit activation pattern in vastus medialis was reduced in degenerative conditions and post ACLR individuals (15, 16). Proprioception was also impaired following an ACL injury in line with muscle surface EMG and gait parameters (17). Observations made by Kaya *et al*. (18) highlighted the incremental changes in the elastographic property of quadriceps using ultrasound elastography following ACLR. They have noted an altered recovery pattern with VMO in response to physical rehabilitation compared to the rest of the counterparts.

In our study, the weakness and alterations in the VM might have facilitated the adaptive neuro-muscular activation strategies from other components of the extensor mechanism. These adaptive coping strategies following injury and ACLR might have improved overall knee functional score. This improvement was noted irrespective of reduction in CSA and MVIC of VM with a mean difference of 31.29, almost double the Minimum Detectable Change (MDC) for the IKDC tool in ACL injuries in the present study (19). However, participants with less reduction in CSA had a better knee functional score.

The study's strength was the observation of adaptive coping strategies despite reducing the structural and physiological morphologies of VM.

However, there were a few limitations. First, the duration of follow-up was short. Second, since both types of grafts (BPTB and hamstring) were selected, the impact of either of them might have influenced the outcome. Third, the time frame from injury to the time of surgery was not homogenized. Hence the waiting time could have altered the observation. Lastly, the females included in this study were less and hence generalization of our observation needs a critical outlook.

CONCLUSIONS

To conclude, our study observed an inverse relationship in patient-reported functional outcome measures and structural and physiological morphology of VM in individuals who have undergone ACLR. Six months after ACLR, the CSA was reduced by three times that of the control, while the MVIC values were lowered by two times. The patient-reported functional outcome measures, on the other hand, improved significantl .

FUNDINGS

None.

DATA AVAILABILITY

Data are available under reasonable request to the corresponding author.

CONTRIBUTIONS

GB: conceptualization, design, analysis, manuscript preparation and revision. GK: data collection, analysis and literature search. MJ: conceptualization, supervision, manuscript writing and editing. TR: statistical analysis, interpretation and critical review. DB: materials, supervision and interpretation. GSG: supervision, manuscript preparation and editing.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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