

Modified Pulvertaft on Weave Technique Restores Full Active Knee Extension in Patients With Large Chronic Quadriceps Tendon Rupture: A Case Series



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Purpose: We aimed to investigate the clinical and functional outcomes, including maximal and explosive strength, after chronic quadriceps tendon rupture repair with Modified Pulvertaft on Weave (MPW) technique. **Methods:** Knee joint range of motion (ROM), patella height, thigh circumference, and Lysholm and International Knee Documentation Committee (IKDC) scores were assessed preoperatively and postoperatively. The knee extensors maximal (isokinetic peak torque and isometric maximal voluntary contraction (MVC) torque) and explosive strength—rate of torque development (RTD) early [RTD₅₀ and RTD₁₀₀] and late [RTD₂₅₀—were performed. We assessed the thigh circumference and vastus lateralis muscle thickness (MT) as indicators of quadriceps muscle mass, and the voluntary quadriceps activation using surface electromyography (EMG₅₀). **Results:** Nine patients (mean age: 53 ± 11 years) took part in the study. We observed a significant increase in the knee active ROM and a decreased extension deficit (both, $P < .001$), but not for pain ($P = .07$), IKDC ($P = .07$), and Lysholm ($P = .21$) after the surgery. We did not observe a difference between involved ($n = 8$) and uninvolved ($n = 10$) limbs for ROM, thigh circumference, and MT. We observed differences for extensors peak torque, MVC torque, and late RTD (all, $P < .05$). However, we did not observe differences for early RTD and EMG₅₀. Significant positive correlations were observed for RTD₅₀ ($\rho = .80$) and RTD₁₀₀ ($\rho = .81$) vs EMG₅₀. Both the IKDC and Lysholm were better correlated with the early than with later RTD. **Conclusions:** The MPW reestablished the active knee extension. The same level of quadriceps muscle mass was observed in both limbs, suggesting a lack of hypotrophy due to the injury. Although the involved limb had demonstrated lower knee extensors maximal strength, they demonstrate an equivalent early RTD when compared to the uninvolved limb. The early RTD seems to be better correlated with the patient's functionality than the later RTD and maximal strength. **Level of Evidence:** IV, case series.

Introduction

The knee extensor mechanism comprises the quadriceps muscle and tendon, patella bone, and patellar tendon.¹ The disruption of any of those structures leads to loss of active knee extension and joint stability.² When a quadriceps tendon rupture is surgically repaired within 3 weeks, an excellent functional clinical outcome is expected.³⁻⁵ Otherwise, delayed treatment (>3 weeks) could lead to unsatisfactory clinical outcomes, as quadriceps atrophy/weakness, incomplete knee extension, and patient dissatisfaction with the overall knee function.^{4,6} Those worse clinical outcomes have been attributed to the tendon edge's retraction and its fixation by scar tissue, which makes distalization and surgical repair more difficult.^{7,8}

Although multiple techniques have been outlined in the literature,⁹⁻¹¹ the Codivilla's technique has been considered the classic surgical technique for the

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The authors report no conflicts of interest in the authorship and publication of this article. Full ICMJE author disclosure forms are available for this article online, as [supplementary material](#).

Received May 25, 2021; accepted January 16, 2022.

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0749-8063/21741/\$36.00

<https://doi.org/10.1016/j.arthro.2022.01.023>

treatment of chronic quadriceps tendon rupture.¹² However, it is regarded as a difficult and highly demanding approach to treat patients with degenerative tendon modifications.^{7,13} Alaia et al.¹⁴ proposed an alternative surgical approach using an allograft to pull the retracted tendon and bone anchors to fix it to the patella. Recently, it has been demonstrated that the Modified Pulvertaft on Weave (MPW) technique—using an autologous tendon graft and replacing bone anchors with transosseous sutures—would make it possible to obtain good functional outcomes.¹⁵ Those modifications brought some advantages to the original surgical technique, such as the use of autologous tissue, allowing a better healing process¹⁶ and reducing the intrinsic risk of pathologies transmission from the tissue bank,¹⁷ besides not using bone anchors for fixation, which turns the procedure less expensive.¹⁸

Isokinetic evaluation of the knee extensors and flexors is commonly employed to assess the maximal strength—generally, the instantaneous peak torque—in patients who have undergone orthopedic surgical treatment. We were able to find only a few studies using isokinetic tests in patients with repaired quadriceps tendon,^{4,19–21} and they all agreed that there is a high quadriceps maximal strength deficit in comparison to the uninjured limb.

Although maximal strength is a relevant variable, such force level probably will not be reached during daily tasks, merely because the time available to exert strength is very restricted (<300 ms).^{22,23} The capacity to produce strength within short-time periods can be assessed as the rate of torque development (RTD), which in turn, can be labeled as early (periods <100 ms) and late RTD (>200 ms).²⁴ It is known that the early RTD is highly correlated to voluntary muscle recruitment and their firing rate.^{25,26} While late RTD is closely related to maximal strength^{26–28} and muscle mass.²⁹ Although RTD has been evaluated in subjects with different orthopedic injuries (e.g., ACL rupture, knee, and hip osteoarthritis)^{30,31} patients who underwent a quadriceps tendon repair were not yet evaluated.

Thus, we aimed to investigate the clinical and functional outcomes—including maximal and explosive strength—after chronic quadriceps tendon rupture repair with MPW. We hypothesize that the MPW can restore active knee extension, improve the functional level, reduce pain, and reestablish muscle mass. However, weakness might be expected on the injured limb due to the intrinsic delay in the disease treatment.

Methods

Subjects

Continuous patients of both sexes were selected from the hospital's records (screened period between

January 2016 and April 2019). Patients were included if they were a minimum age of 18 years old and presented chronic (>3 weeks) quadriceps tendon rupture treated surgically with the MPW. The exclusion criteria were a surgical treatment different from MPW and an inability to attend to data acquisition. The study was approved by the Institutional Ethics Board (no. 67188117.0.0000.5273).

Experimental Protocol

Knee joint range of motion (ROM), patella height, thigh circumference, and knee functional scores were assessed from the individual's medical records preoperatively—acquired following the institutional standardized protocol (only the involved limb—performed by J.L.R.F.). Postoperatively, those measures were repeated (both limbs—performed by J.L.R.F. and M.B.C.). Also, measures of maximal and explosive strength were performed (performed by C.T.L., U.F.G., and V.R.A.C.). Moreover, we assessed the vastus lateralis muscle thickness (MT)—(performed by C.T.L.) as an indicator of quadriceps muscle mass—and the voluntary quadriceps activation using surface electromyography (EMG; performed by U.F.G.). All of the measurements were conducted on both lower limbs, being the dominant one self-defined as the preferred kicking leg. Postoperative measures were carried out in a single session lasting ~60 min (between November 2019 and February 2020).

Surgical Procedure and Rehabilitation Process

A longitudinal (10–15 cm) incision was made over the quadriceps tendon area, exposing the quadriceps tendon, patella, and patellar tendon. A second incision (4 cm) was performed to expose the tibial insertion of the medial hamstrings, allowing the semitendinosus tendon dissection for posterior harvesting. In the sequence, we proceeded with quadriceps tendon proximal stump dissection, including the resection of the fibrotic tissue between the tendon and proximal patellar pole (Fig 1A). After that, a transverse bone tunnel was created at the proximal one third of the patella, using a 5-mm cannulated drill, drilling the patella in its center (lateral view) from medial to lateral (Fig 1, B–E). With the 5-gauge drill still inside, we created three parallel longitudinal tunnels to threading needles inserting, leaving the repair wire on the carrying handle at the proximal end of each of these tunnels (Fig 1, F–H). The quadriceps tendon's middle section was then sutured (Krackow sutures) with two polyester threads (no. 2 Ethibond - Ethicon) (Fig 1I). The four wires at the distal end of the quadriceps tendon were retained. Three to four punctiform holes were created in the medial and lateral borders of the quadriceps tendon (Fig 1J) for threading the autograft, which was passed through the transverse tunnel,

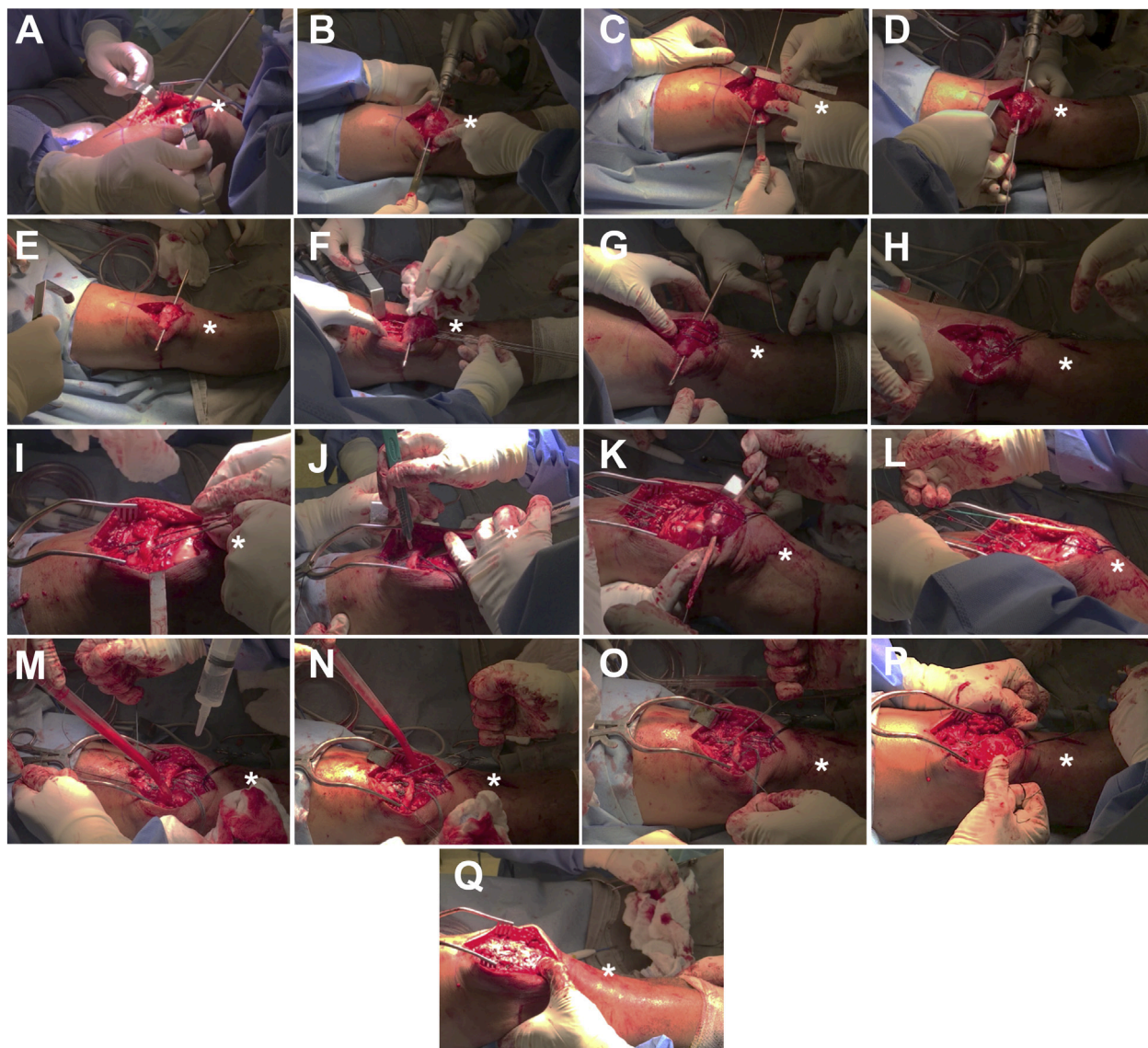
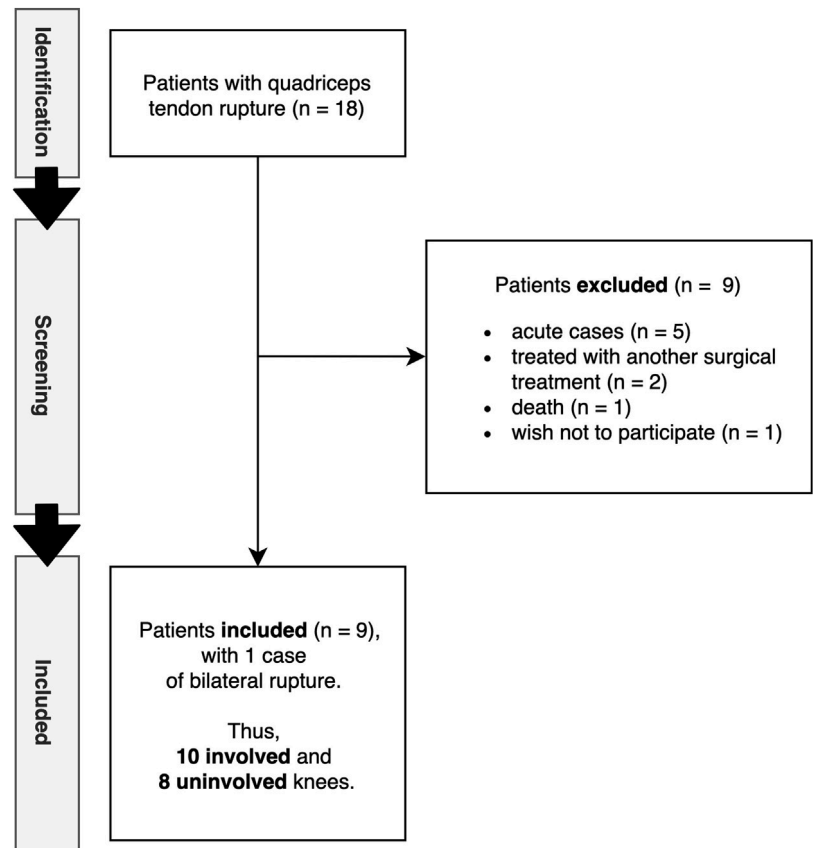


Fig 1. Modified Pulvertaft on Weave procedure step-by-step. The technique begins with the quadriceps tendon proximal stump dissection and resection of the fibrotic tissue (A). Transverse bone tunnels are created at the patella using a 5-mm cannulated drill (B-E). Then, three parallel longitudinal tunnels are created to insert the threading needles, leaving the repair wire at the proximal end of each tunnel (F-H). Krackow sutures of quadriceps tendon's middle section (I). Wires retention at the distal end of the quadriceps tendon and the creation of three to four punctiform holes for autograft threading (J). The autograft passes through the transverse tunnel (K-L), and its ends are threaded through the holes in the borders of the quadriceps tendon, ensuring the anterior direction of the tip of the tendon after the final thread (M). Traction, cross-over, and suture of the distal ends of the autograft over the quadriceps tendon to reduce the anterior gap, leaving a residual gap in its central portion (N-O), which is closed, forming a transosseous suture in the distal pole of the patella (P). The suture is then tested by flexing the knee up to 30° (Q). *Indicates the distal portion. All pictures were taken from the same patient and from the right leg.

leaving two symmetrical extremities (Fig 1, K and L). Those autograft ends were then threaded through the holes in the medial and lateral borders of the quadriceps tendon, ensuring that the tip of the tendon after the final thread was directed anteriorly (Figure 1M). The distal ends of the autograft were then tractioned, crossed over, and sutured over the quadriceps tendon (in a locking X formation) to reduce the anterior gap in the tendon, with only a residual gap in the central

portion of the tendon (Fig 1, N and O). The residual central gap was, finally, closed by pulling on the four polyester suture strands (from the previous Krackow sutures), forming a transosseous suture in the distal pole of the patella (Fig 1P). Then, we tested the suture by flexing the knee up to 30° (Fig 1Q). All of the patients accomplished the same postoperative rehabilitation protocol—using a knee brace locked in full extension for 6 weeks—and received the general

Fig 2. Study flowchart.

rehabilitation guidelines up to 6 months post-operatively (Supplemental 1).

Range of Motion, Pain Level, and Knee Functional Questionnaires

Active knee extension ROM—expressed as full flexion-extension and extension deficit—was acquired using a universal goniometer.³² Pain level was evaluated using a visual analog scale (VAS), within 0 (complete absence) to 10 points (worse pain possible).³³ Knee functional status was assessed using both the Lysholm³⁴ and the International Knee Documentation Committee (IKDC).³⁵

Patellar Height, Osteophytes Presence, and Thigh Circumference

Patellar height was measured preoperatively (24 hours before the surgery) and postoperatively (immediately after) in the knee radiograph's lateral view (MDViewer2000, NEC Display Solutions, Japan). We used the patellar height measurement index proposed by Insall-Salvati.³⁶ The presence of osteophytes was evaluated qualitatively in the same radiograph (performed by J.L.R.F.). Thigh circumference was measured with the patient in the orthostatic position with a measuring tape positioned 10 cm from the patella upper pole.³²

Maximal Strength

Thigh muscle strength was assessed using an isokinetic dynamometer (HUMAC NORM II, CSMi Solutions, Stoughton, MA). The participants were seated with hips flexed $\sim 90^\circ$ with trunk and thighs stabilized with nonelastic straps, and the knee joint was aligned with the device axis of rotation. Participants performed a warm-up/familiarization set comprising five progressive-intensity repetitions (20, 40, 60, 80, and 100% of subjective effort). Followed by five maximum exertions at $60^\circ/\text{s}$ to obtain the knee extensors and flexors peak torque.

Explosive Strength and Voluntary Muscle Early Activation

After a 5-min rest, the patients performed the knee extension explosive maximal voluntary contractions (MVC; 3 trials, lasting 3 s at 90° of knee flexion, sampling: 1 kHz) with synchronously recording of surface quadriceps EMG acquisition (EMG 830c, EMG System do Brasil, São Paulo, Brazil; gain: 1000, band-pass filtered: 20-500 Hz, sampling: 1 kHz). Subjects were instructed to produce force "as fast and hard as possible".²⁴ The surface EMG signal was recorded from the vastus lateralis (VL), rectus femoris (RF), and vastus medialis (VM) by pairs of silver chloride electrodes

Table 1. Patients' Demographic and Clinical Data

Patient	Age	Sex	Comorbidities	Injured Knee	Elapsed Time - Injury to Surgery (Months)	Elapsed Time - Surgery to Postoperative Evaluations (Months)	Osteophytes
#1	59	M	CKD	Right	48	42	No
#2	53	M	CKD	Right/Left	16	37	No
#3	50	M	SAH	Right	14	8	No
#4	52	M		Right	10	40	No
#5	55	M	CKD	Right	26	30	No
#6	73	M	SAH DM	Right	27	20	No
#7	37	F	SAH	Right	8	36	No
#8	41	M	SAH	Right	18	10	No
#9	68	M	SAH DM	Right	46	8	Yes

CKD, chronic kidney disease; DM, diabetes mellitus; F, female; M, male; SAH, systemic arterial hypertension.

(RedDot, 3M Corp). The signals were processed by custom-built software, as described elsewhere.²⁶ The early (RTD₅₀, RTD₁₀₀) and late RTD (RTD₂₅₀) were calculated at 50, 100, and 250 ms from contraction onset, respectively.²⁴ The EMG₅₀—root mean square value of a 50-ms window immediately preceding contraction onset—was calculated as previously described.²⁶

Vastus Lateralis Muscular Thickness

The images were acquired (7.5 MHz, 40-mm linear array probe, B-mode, SSD900, ALOKA, Japan) with the probe positioned perpendicularly to the femur's longitudinal axis at one-half of the distance between the greater trochanter and the superior edge of the patella.³⁷ VL MT was determined as the linear distance between the upper and lower muscle's aponeurosis (ImageJ software, version 1.51, National Institutes of Health, End User Agreement).²⁶

Statistical Analysis

Preoperative and postoperative ROM, VAS, patellar height, thigh circumference, and functional scores were compared to evaluate the effects of surgical reconstruction on knee function and pain at the involved knee. Besides, comparisons were performed between limbs (involved vs uninvolved) for ROM, thigh circumference, MT, maximal and explosive strengths, and EMG₅₀ at the postoperative moment. The non-parametric Mann-Whitney *U*-test was used for all calculations. The association between EMG₅₀ and RTDs, as between functional scores and strength (maximal and explosive) of the involved knees were evaluated by Spearman's coefficient (ρ). The significance value was set at $P < .05$. All calculations and graphs were performed using GraphPad Prism (GraphPad Software, Inc., v. 5, San Diego, CA).

Results

Initially, a total of 18 patients were diagnosed with quadriceps tendon rupture. Of those, five were acute cases, two were treated with another surgical technique, one died, and one did not wish to participate. Therefore, of 11 patients who met the inclusion criteria,

two were lost to follow-up, and then, 9 patients remained eligible and provided written informed consent (1 woman and 8 men, means $\pm$ SD — age: 53 ± 11 years; height: 171.3 ± 7.2 cm, body mass: 95.9 ± 16.9 kg) (Fig 2). All of the remaining subjects were indicated to a surgical reconstruction due to loss of full knee extension. They also self-reported right lower limb dominance and did not have any other injuries at the contralateral limb, except one subject who demonstrated bilateral quadriceps rupture, which was simultaneously reconstructed at the same surgery. Hence, a total of 10 involved and 8 uninvolved knees were analyzed, and the interval from injury to surgery was 24 ± 15 months and between surgery and postoperative evaluations was 26 ± 14 months (Table 1).

Preoperative Versus Postoperative ROM, Pain, Functional Scores, and Patella Height

We observed a significant increase in the full active ROM (preoperative: $79.5 \pm 14.2^\circ$, postoperative: $109.0 \pm 15.4^\circ$; $P < .001$) and a decrease on knee extension deficit (preoperative: $46.5 \pm 10.0^\circ$, postoperative: all obtained 0° ; $P < .001$). We did not observe a difference between preoperative and postoperative pain levels (preoperative: 2.3 ± 2.4 points, postoperative: 1.8 ± 2.0 points; $P = .07$), IKDC (preoperative: 30.3 ± 9.9 points, postoperative: 43.6 ± 12.3 points; $P = .07$), and Lysholm (preoperative: 55.7 ± 14.3 points, postoperative: 65.6 ± 19.1 points; $P = .21$) scores. We also observed an increase in the patella height (preoperative: $.55 \pm .22$ and postoperative: $.77 \pm .17$; $P < .001$) (Fig 3).

Involved Versus Uninvolved Knee Postoperative ROMs, Thigh Circumference, Muscle Thickness, Maximal and Explosive Strength, and Early Muscle Voluntary Activation

We did not observe differences between involved and uninvolved limbs for ROM (involved: $111.0 \pm 16.0^\circ$ and uninvolved: $116.3 \pm 5.2^\circ$; $P = .53$), thigh circumference (involved: 47.01 ± 5.2 mm, uninvolved: 50.4 ± 6.9 mm; $P = .30$), MT (involved: 18.7 ± 3.7 mm, uninvolved: 23.3 ± 6.9 mm; $P = .05$). We also did not

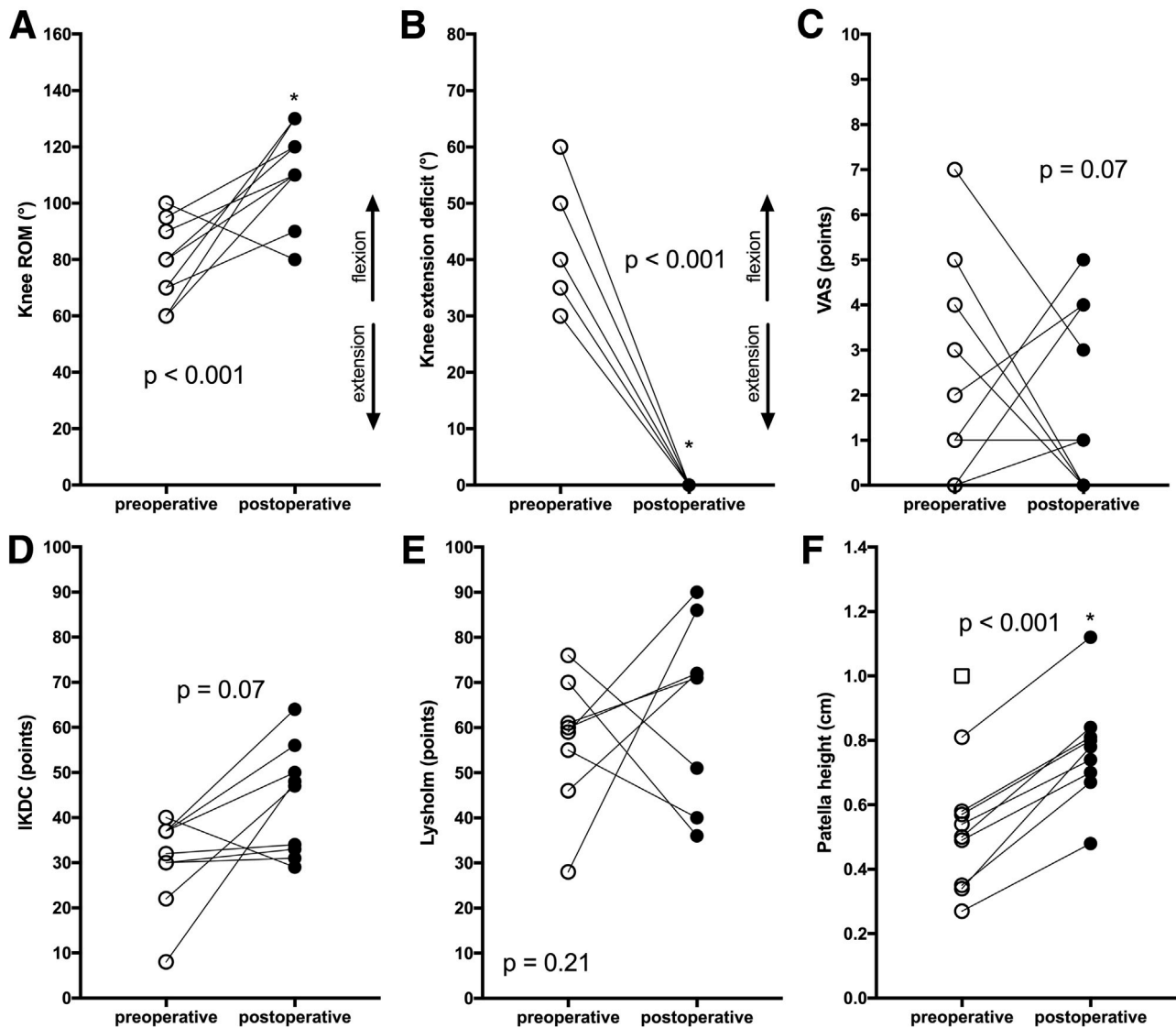


Fig 3. Involved knee range of motion, knee extension deficit, pain, IKDC, Lysholm, and patella high measured at the pre and postoperative. (A) Full knee active range of motion (ROM). (B) Knee extension deficit. (C) Visual analog scale (VAS) for pain. (D) International Knee Documentation Committee (IKDC). (E) Lysholm. (F) Patella height. *Significantly different from the preoperative.

observe differences for flexors peak torque, RTD_{50} , RTD_{100} , and EMG_{50} (Fig 3). However, there were observed differences for extensors peak torque, MVC torque, and RTD_{250} (Fig 4).

Correlation Between Explosive Strength and Muscle Voluntary Activation

We observed a significant positive strong correlation for RTD_{50} ($p = .80$) and RTD_{100} ($p = .81$) vs EMG_{50} , but not for RTD_{250} vs EMG_{50} ($p = .44$).

Correlation Between Maximal and Explosive Strength With Knee Functional Scores

We observed a significant positive strong correlation between IKDC vs MVC torque ($p = .70$), RTD_{50}

($p = .90$), and RTD_{100} ($p = .80$). Similarly, Lysholm vs RTD_{50} ($p = .80$), RTD_{100} ($p = .87$), and RTD_{250} ($p = .70$). We did not observe additional other significant correlations (Fig 5).

Discussion

The main finding of this study was the decrease of knee extension deficit—and consequently, an increase in total ROM after the quadriceps tendon reconstruction surgery—with all of the patients obtaining full active knee extension of the involved limb. Also, all the patients demonstrated a significant increase in the patellar height postoperatively, reaching the expected threshold of normality—0.8 to 1.2 cm defined for the Brazilian population.^{36,38,39} However, those

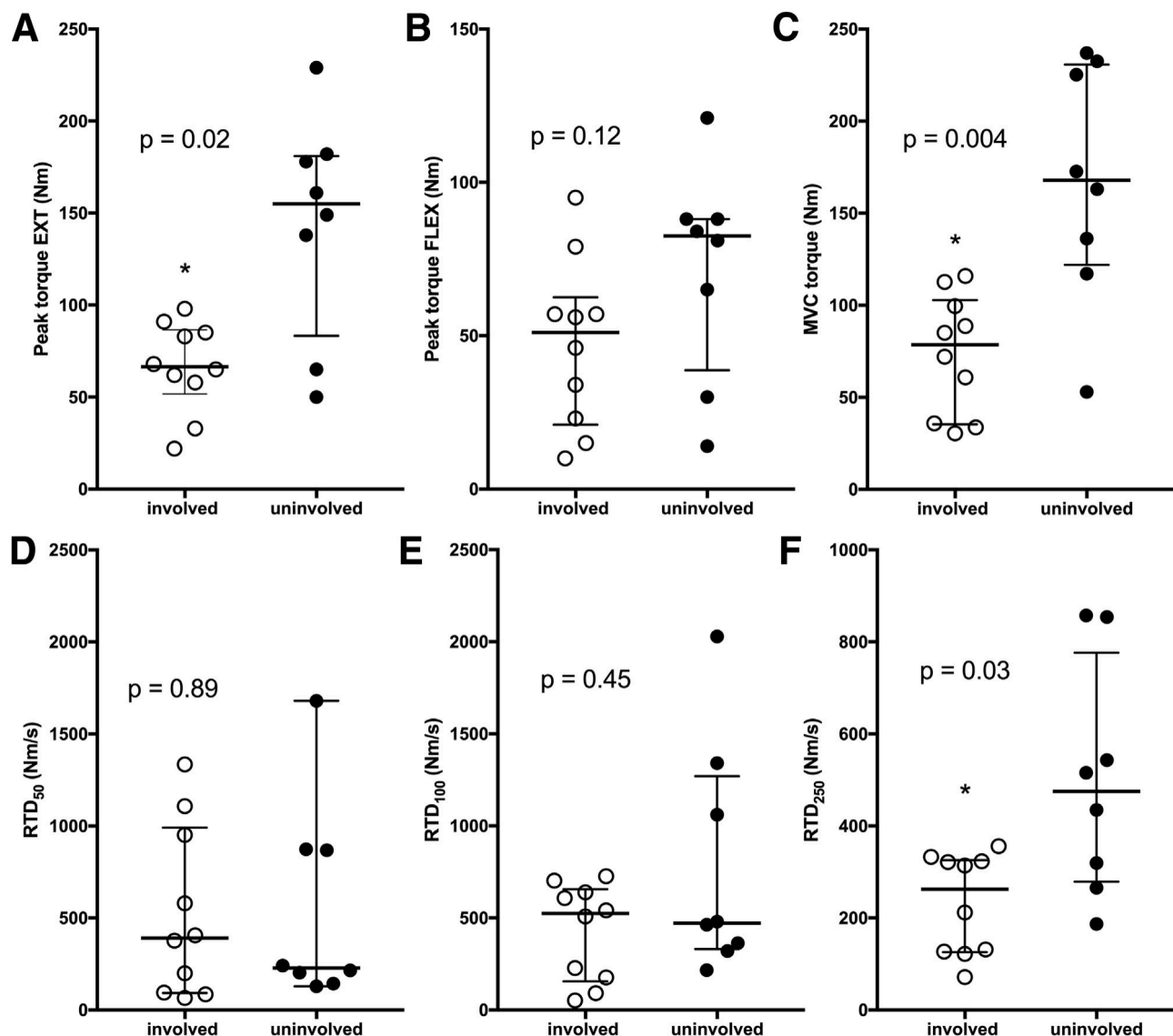


Fig 4. Maximal and explosive strength measured in involved and uninvolved limb postoperatively. Values demonstrated in median (horizontal line) and interquartile range (whiskers). (A) Knee extensors peak torque (EXT). (B) Knee flexors peak torque (FLEX). (C) Maximal voluntary contraction (MVC) torque. (D) Rate of torque development (RTD) at 50 ms. (E) RTD at 100 ms. (F) RTD at 250 ms. The A, B, and C are maximal, while D, E, and F are explosive strength measurements.

improvements were not followed by any significant changes in pain level and functional scores, as hypothesized. Interestingly, we also did not find any differences between limbs postoperatively regarding total knee ROM and muscle mass-related variables (thigh circumference and MT), suggesting the return of the variables to the normal noninjured values. Together, those improvements evidence the effectiveness of the MPW in reestablishing the knee extensor mechanism active movement and morphology in patients with chronic quadriceps tendon ruptures.

Although we did not find differences in pain and functional scores postoperatively, it should be highlighted that most of the patients improved their scores. In fact, after surgery, only three subjects (#3, #6, and #

8; see Fig 2, D and E) got the functional scores worse or unaffected, and the lack of statistical significance probably reflects the study's small sample size. Unfortunately, we are unable to explain specifically why those subjects did not improve the pain and functional status. However, a plausible explanation can lie in the high injury chronicity and the comorbidities demonstrated by the patients: chronic kidney disease, systemic arterial hypertension, and diabetes mellitus. It is well known that those diseases are associated with inferior clinical outcomes due to secondary health issues (such as muscular atrophy, tiredness, and difficulty walking).^{40,41} Those conditions might negatively affect functional scores because those questionnaires rely on questions regarding physical activity demands, which

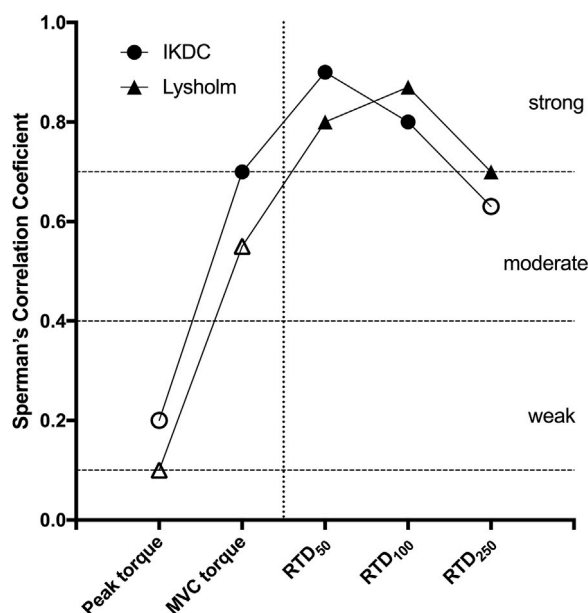


Fig 5. Measured Spearman's correlation coefficients between the IKDC and Lysholm scores with maximal and explosive strength measures. Rate of torque development at 50 ms (RTD₅₀). RTD at 100 ms (RTD₁₀₀). RTD at 250 ms (RTD₂₅₀).

cannot be done due to a general health condition instead of an orthopedic disability.

Although knee function was reestablished, and the patients demonstrated a lower maximal strength of knee extensors—both, peak torque and MVC torque. This corroborates previous investigations,^{4,19-21} which observed quadriceps strength deficit after a quadriceps tendon reconstruction. Although our results are in line with previous findings, it should be kept in mind that those studies mixed acute and chronic cases in the sample, with different surgical techniques—being the trans-osseous suture most frequently, but none with Pulvertaft on Weave technique—making a deeper comparison with the present results difficult. Interestingly, we did observe a difference in knee flexors between limbs. This provides evidence that muscle group strength was not affected by the graft donation.

Although the interest in investigating explosive strength has increased recently,²⁴ including in patients after undergoing surgical procedures,^{42,43} we did not find previous studies evaluating knee extensors RTD in patients after quadriceps tendon reconstruction. Interestingly, we did not observe differences between limbs in the early RTDs, but, instead, a significantly lower late RTD was found. The former can be explained by the lack of difference in the quadriceps early voluntary muscle activation, while the latter can be explained by the significant lower maximal strength of involved knee extensors observed here. This way of thinking is in agreement with the previous experimental observations that demonstrated an intrinsic relationship

between early RTD and the motor units discharge pattern at contraction onset,^{25,28} while the late RTD was better associated with maximal strength capacity, and all of the variables associated with it (e.g., muscle mass, physiological cross-sectional area).^{27,29,37}

Moreover, we observed a strong linear positive relationship between EMG₅₀ and early RTD and a moderate correlation with the late RTD, reinforcing previous observations,²⁶ and expanding to a specific orthopedic population. Moreover, we also observed a strong positive correlation between both IKDC and Lysholm scores with early RTD, while moderate correlations were observed with MVC torque and late RTD, and a weak correlation with extensors peak torque. In other words, the early RTD was better associated with the functional scores than the late RTD and maximal strength. This has clinical relevance and suggests that the patients' function can be benefited from improvements in early RTD.^{44,45} Thus, improving the explosive strength should be considered a goal during the rehabilitation protocol in parallel with the maximal strength and muscle mass regain.

Although previous studies had suggested a link between osteophytes presence and quadriceps tendon rupture,⁴⁶⁻⁴⁸ only one of our patients demonstrated osteophytes (# 9). Therefore, we are unable to use this variable for further analysis. The MPW¹⁵ introduced mainly two changes to the technique proposed by Alaia et al.¹⁴: the use of autologous graft and trans-osseous sutures. Those factors summed to the good clinical and functional outcomes observed here advocate in favor of the MPW as a valuable option for the treatment of chronic quadriceps tendon disruption.

Limitation

One of the study's drawbacks is the small sample size. Another limitation was the higher range of age and the time elapsed between the surgery and evaluation. Moreover, strength results must be analyzed keeping in mind the cross-sectional design, and the fact that the uninvolved limb was used as a control. Also, it should be mentioned that there were no tissue biomechanical studies—regarding the reconstructed tendon—after the MPW, which can expand the confidence upon the surgical technique.

Conclusions

The MPW reestablished the active knee extension. The same level of quadriceps muscle mass was observed in both limbs, suggesting a lack of hypotrophy due to the injury. Although the involved limb had demonstrated maximal strength of the lower knee extensors, they demonstrated an equivalent early RTD when compared to the uninvolved limb. The early RTD seems to be better correlated with the

patient's functionality than the later RTD and maximal strength.

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