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Original Investigation

A focus on exercise prescription and assessment for a safe return to sport participation following a patellar tendon reconstruction in a soccer player.

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Purpose: The aim of this study was to analyse a 6-month kinesiological intervention after patellar tendon reconstruction. The kinetics, kinematics, and neuromuscular differences between operated (OL) and non-operated limbs (N-OL) were examined over time in a soccer player.

Methods: The assessment took place at three months (T0) and nine months (T1) after the reconstruction. This comprised an assessment of the range of motion (ROM), gait analysis through angle-angle diagrams, postural control, neuromuscular assessment during whole-body vibration (WBV), and unilateral-bilateral maximal voluntary isometric contractions (MVICs) synchronised with surface electromyography (sEMG).

Results: The angle-angle diagrams at T1 show that the area and perimeter of the N-OL and OL diagrams increased, especially the area and perimeter of the knee-ankle diagram in OL. Furthermore, the postural control at T1 indicated an increase in different conditions. The root mean square (RMS) of sEMGRMS obtained during WBV revealed a significant alteration in the neuromuscular patterns in the OL at T1. The increase in the vastus lateralis (VL) and lateral gastrocnemius (LG) activities was accompanied by a decrease in the biceps femoris (BF) and tibialis anterior (TA). The peak of force and the rate of force development during MVICs showed a slight difference between OL and N-OL at T1. Furthermore, sEMG$_{RMS}$ activity synchronised with MVICs showed a slight difference between the OL and N-OL in the extensors (VL, VM, and RF) and flexors (BF) muscles at T1.

Conclusions: The kinetic, kinematic, and neuromuscular variables have shown improvements at T1 compared to T0. Anyway, a 6-month individualised kinesiological intervention, following a patellar tendon reconstruction, reveals that minor alterations in the neuromuscular pattern remain in the OL. These results help kinesiologists manage the functional recovery after patellar tendon reconstruction.

Keywords: Angle-Angle diagrams, Postural Control, Whole-Body Vibration, Maximal Voluntary Isometric Contraction, Knee Injuries

Introduction

The patellar tendon is a strong and sturdy band of fibrous connective tissue that originates from the bottom of the patella and extends down to attach to the tibial tuberosity, a bony prominence on the front surface of the tibia.[1] The patellar tendon is a remarkable structure that provides essential support and stability to the knee joint.[1] The incidence of isolated patellar tendon rupture (PTR) is approximately .68/100.000 per year of all soft tissue injuries, requiring immediate repair to avoid significant muscle retraction and tendon fibrosis. The literature indicates that isolated PTRs are more common in young individuals (below 45 years of age) who are physically active rather than inactive. These data show that males are six times more likely to have isolated PTRs than females.[2,3] Patellar tendon tears are attributed to several factors, including tendon degeneration resulting from repetitive microtrauma, rapid quadriceps contractions during knee flexion, and repetitive high-stress cycles of loading and unloading.[4–6] This injury has been extensively examined in various sports populations, with a particular emphasis on how performance relative to specific sports features may be affected following reconstruction.[6]

The American football players exhibit a lower percentage (around 60%) to return to sport competition, with a performance decrease in the two years following the return to competition (i.e., touchdowns, interceptions, number of games played, rushing yards and passing yards). The low percentage and their decrease in performance appear to be related to the high BMI values and to the position on the field (i.e., running backs, receivers). Furthermore, athletes with a high BMI who perform tasks with impact at ground (i.e., jumping, landing) generate a high load in their reconstructed patellar tendon, which explains the worsening of the performance and the early end of sports careers.

The basketball players exhibit a high percentage (approximately 93%) of returning to competition, and their performance is unaffected. However, the number of games played in the three consecutive seasons following injury is lower than the number played before injury.[6] It appears that the decrease in games played by basketball players is not related to the injury, but rather to an age factor. Indeed, the injury occurs at a later age compared to other athletes, such as soccer or football players.[6]

The return to sport participation rate for soccer players is high (around 95%), but the performance following patellar tendon reconstruction is characterised by a reduced number of goals, assists, and shots. Soccer players experienced a reduction in goals and assists after returning to competition, which could be due to cleats-surface interactions in sport-specific tasks (i.e., kicking the ball or running). The forces that arise from the cleats-surface interactions augment the ground reaction forces, which in turn exert stress on the repaired patellar tendon, thereby limiting its short-term performance.[7]

The impact of a ruptured patellar tendon on athletic performance and its management has never been thoroughly assessed. The literature indicates that common issues encountered during the return to sport following PTR encompass modifications in the following areas: hip and ankle joint hypomobility,[8,9] which may serve as a compensatory mechanism for impaired knee function; muscular strength imbalance, and functional reduction of knee ROM (primarily due to surgery and postoperative immobilization).[10] Therefore, assessments should be objective in order to accurately assess the athlete's degree of impairment.

The functional outcomes considered for a safe return to sport participation following patellar tendon reconstruction include subjective variables through different self-reported questionnaires (SRQ) like the Lysholm Gillquist scale, the Tegner activity scale, and the International Knee Documentation Committee (IKDC). The objective variables comprise of flexibility, range of motion, dynamic or isometric strength test, gait analysis, and postural control.[3,11–18] However, due to the rarity of patellar tendon rupture, the literature lacks specific guidelines for the assessment and intervention. Strength assessment or strength and postural control assessment have been reported by some authors.[3,14,18] Rosteius et al.[17] were the only ones who studied gait analysis and surface electromyography (sEMG) after patellar tendon reconstruction.

Furthermore, following peripheral joint injury, the proprioception appears altered, resulting in deficits in the neuromuscular control.[19,20] We know that the soft tissues around the joints have many mechanoreceptors that tell the brain what's happening when the joint moves. The mechanoreceptors inside these tissues are disrupted when a peripheral joint injury occurs. Common neuromuscular consequences are reduced muscle strength and altered muscle activation.[19] Following joint injury, Ward et al.[19] observed an increased spinal reflex activity bilaterally, suggesting that the higher reflex activity represents a compensatory strategy to maintain voluntary activation in the muscles involved.

During the whole-body vibration (WBV), the proprioceptive system is strongly stimulated.[21] WBV induces a greater vastus lateralis and vastus medialis activation in the knee with the ACL reconstructed when compared to the healthy knee.[21] The mechanism is mediated by muscle spindles that detect the micro stretch-shorten cycles and send the afferent information to the sensorimotor cortex, which in turn integrates the input at different levels of the central nervous system to elaborate the motor output.[22]

A large discrepancy in the functional outcomes used emerges from the literature review, suggesting that the sEMG response to WBV could be used as an additional functional outcome to detect any changes in the neural strategy and proprioceptor functioning following trauma. In any case, the other functional outcomes reported in the literature may provide fundamental insights into locomotion, balance, and muscle strength during the recovery process.[3,11–18] Other critical points that emerged from the literature review include the lack of detailed and specific kinesiological protocols, and the fact that functional recovery is assessed at the end of the initiation, but not during.[15,18,23] A picture of the subject condition can be provided by the initial assessment, which allows for individualisation of the intervention. Therefore, the management of functional recovery could be optimised by applying an appropriate workload and monitoring the functional recovery with different and sensitive outcomes.[24] The present case study aims to examine the efficacy of a six-month kinesiological intervention that incorporates kinetic, kinematic, and neuromuscular outcomes in the evaluation process. Over the kinesiological intervention, several measurements were performed, including postural control, gait analysis, neuromuscular responses of whole-body vibration, and maximal voluntary isometric contraction. These measurements provided an accurate evaluation of the adaptive process. The kinesiological intervention was quantified and managed through three different target macrocycles (ROM and proprioceptive recovery, maintaining ROM and isometric strength recovery during the unilateral and bilateral execution, dynamic strength and power recovery).[3] It was hypothesised that a six-month Kinesiological intervention comprising of appropriate kinetic, kinematic, and neuromuscular measurements could establish the timing for a secure return to sport participation in a soccer player who underwent a patellar tendon reconstruction.

Methods

Participants

This case report describes a 28-year-old (Stature: 177 cm, Boby Mass: 70 kg, BMI 22.3 kg/m^2) with several years of training experience who was engaged in a team sport training program three times a week before the injury. The subject underwent two patellar tendon reconstructions on his dominant leg (the right leg). The first injury occurred on May 14, 2022, after a game clash. The subject underwent the first surgical reconstruction in June 2022 with the autologous transplant technique in which the semitendinosus and gracilis muscles were used as grafts. After completing the physiotherapy phase, the subject initiated a kinesiological rehabilitation plan. He reported a sudden, intense pain in the operated limb while engaged in a light running on the field during this phase. The pain was severe enough to prevent the knee from bending, resulting in swelling, stiffness, and functional impediments. A diagnostic examination revealed that the subjects had sustained a second complete lesion of the patellar tendon, resulting from the failure of the newly implanted graft. This second injury occurred on October 31, 2022. The bony components of the knee joint were assessed by X-ray, followed by magnetic resonance imaging to evaluate the soft tissue. The magnetic resonance imaging (MRI) revealed a complete lesion of the patellar tendon at its proximal insertion, with a lesion gap of approximately 7 mm. In November 2022, the subjects underwent a surgical procedure using four trans-osseous sutures in the patella through tunnels. Synthetic resorbable media and metal staples are used to help the graft anchor firmly and prevent relapse, offering safer results for return to sport. After surgery, the subject received an intensive period of three months of physiotherapy focused on restoring mobility, strength, and flexibility to the affected limb. During this time, several subjective functional outcomes were administered, such as the Lysholm Gillquist scale and the Tegner activity scale. Once this phase was complete, he was evaluated and deemed ready to begin the kinesiological intervention in March 2023 following the recommendations reported in the literature.[3] The study was conducted in accordance with the Helsinki Declaration ethical standards and was approved by the internal review board.

Study design

A tailored exercise regimen was used to take into consideration the functional outcomes that defined the subjects' status. The subject visited the laboratory three times. In the first laboratory visit, the subject familiarised himself with the testing procedures. During the second visit, as previously reported in the literature,[25] the subject underwent a 20-minute warm-up, which included both general and specific exercises and then performed the following measurements (T0): gait analysis, postural control, passive range of motion (ROM), and the $sEMG_{RMS}$ activity response to whole-body vibration (WBV) at different vibration frequencies. After six months of kinesiological intervention, we repeated the initial measurements (T1) and included unilateral and bilateral maximal voluntary isometric contractions MIVCs). The recommended intervention lasted for a duration of six months and was divided into three macrocycles, each with its own set of guidelines and objectives (Table 1).[3]

Concerning the Kinesiological intervention, the first macrocycle spanned from the 18th to the 26th week after surgery. It started on March 20th and ended on May 19th. The second macrocycle lasted from the 26th to the 34th week after surgery, considering

Table 1. Kinesiological intervention following a patellar tendon reconstruction

<table>
<tr><td>Kinesiological Program</td><td colspan="8">Horizontal Bike
Squat on wall with Fitball at 45° (Half Squat)
Bilateral Isometric on Unstable Surface
Bilateral Isometric Leg Extension
Leg Curl on Fitball
Isometric Front Lunge on Jellyfish
Squat with Ball Overhead
Adductor Machine
Abductor Machine
Multi Hip Glutes with Pushes
Step Up
Hip Trust
Front and Sides Plank
Crunch, Oblique Crunch, Reverse Crunch
Stretching Lower Limbs (Static and Dynamic)</td><td colspan="8">Horizontal Treadmill
Stepmill
Unilateral Isometric on Right and Left Unstable Surface
Bilateral Isometric on Bosu
Sumo Squat with Kettlebell
Leg Press (Bilateral and Unilateral)
Leg Curl (Bilateral and Unilateral)
Sitting Calf
Leg Extension Bilateral and Unilateral
Alternating Forward Lunges with Medical Ball
Alternating Forward Lunges on Bosu
Squat Jump
Lat Pull Down
Vertical Pull-Ups
Row Machine
Shoulder Press
Crunch, Oblique Crunch, Reverse Crunch
Stretching Lower Limbs (Static and Dynamic)</td><td colspan="5">Horizontal Treadmill
Stepmill
Bilateral and Unilateral Squat on Bosu
Bilateral and Unilateral Isometric Squat on Bosu
Leg Extension (Bilateral and Unilateral) Isometric
Leg Press (Bilateral and Unilateral) Isometric
Squat Jumps
Counter Movement Jumps
Leg Curl
Drop Jumps
Adductor and Abductor Machine
Alternating Forward Lunges on Bosu
Glute Machine
Stretching Lower Limbs (Static and Dynamic)</td></tr>
<tr><td>Macrocycles</td><td colspan="8">1° Macrocycle
(March 20-May 19)</td><td colspan="8">2° Macrocycle
(May 22-July 28)</td><td colspan="5">3° Macrocycle
(August 1-August 30)</td></tr>
<tr><td>AIM</td><td colspan="8">• Proprioceptive stimulation
• ROM Recovery
• To increase Strength (40-60% 1RM) in Lower Limb</td><td colspan="8">• To Increase Strength Upper Limbs
• To Increase Dynamic Strength and Power in Lower Limb
• ROM Recovery</td><td colspan="5">• To Increase Strength (70-90% 1RM)
• Maintaining ROM
• To Increase Power</td></tr>
<tr><td>Weeks after the surgery</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td><td>25</td><td>26</td><td>27</td><td>28</td><td>29</td><td>30</td><td>31</td><td>32</td><td>33</td><td>34</td><td>35</td><td>36</td><td>37</td><td>38</td></tr>
</table>

Abbreviations: 1 Repetition Maximum (1RM); Range of Motion (ROM).

two months of kinesiological intervention, which started on May 22nd and ended on July 28th. The last part of the intervention, i.e., the third macrocycle, spanned from the 34th to the 38th week after the surgery and lasted for only one month of Kinesiological intervention. It started on August 1st and ended on August 30th. The multicomponent program was designed to ensure that the subject could recover his functional abilities and return to sport participation.

Range of Motion (ROM)

The measurement of knee ROM in extension and flexion was conducted using an electrogoniometer connected to a data acquisition unit (MuscleLab-Ergotest Innovation, Langesund, Norway), consistently by the same operator. The subject assumed two distinct positions in both limbs.[26] Initially, passive knee extension (PKE) was measured while the subject assumed a supine position with the hip flexed at 90°, and he attempted to extend the leg maximally. The maximum extent was defined as the upper angle between the line from the head of the fibula to the lateral malleolus of the ankle and a vertical line parallel to the longitudinal axis of the femur. Next, in order to measure passive knee flexion (PKF), the subject assumed a prone position with the knee flexed. The measurement of PKF involved the angle between the line from the head of the fibula to the lateral malleolus and a horizontal line parallel to the longitudinal axis of the femur. The PKE and PKF have showed high values of test-retest reliability (intraclass correlation coefficient, ICC) (.88-.93).[26]

Surface electromyography (sEMG)

The sEMG was recorded in both legs (OL and N-OL) during WBV and MVIC. During the WBV exposure, the sEMG activity was recorded for the vastus lateralis (VL), biceps femoris (BF), tibialis anterior (TA), and lateralis gastrocnemius (LG) of both limbs. During the MVIC, the sEMG activity synchronised was recorded for the vastus medialis (VM), rectus femoris (RF), VL, and BF. The two signals were synchronised through Muscle-Lab software (Muscle-Lab, Bosco-System, Ergotest Innovation, Norway). A full-wave true root mean square (RMS) and a sampling frequency of 100 Hz were used to transform the signal from the preamplifier for sEMG_{RMS} detection. The sEMG_{RMS} was recorded by utilising triode electrodes (T3402 M, nickel-plated brass, with an electrode diameter of 1 cm and an interelectrode distance of 2 cm from Thought Technology Ltd). The electrodes were placed according to the SENIAM (www.seniam.org) instructions, in line with the non-invasive evaluation of sEMG.[27] Before placing the electrodes for sEMG_{RMS} recording, the skin was shaved and cleaned with ethanol to reduce the impedance of the electromyographic signal to less than 5 kΩ. The EMG electrodes and cables were subsequently secured with elastic bands to prevent motion artifacts. The EMG preamplifier characteristics were as follow: voltage supply ±5 VDC; input impedance 2 GΩ; common mode rejection rate 100 dB; gain at 100 Hz 500; 3 dB low-cut frequency, 8 Hz; and 3 dB high-cut frequency 1.2 kHz (Muscle-Lab, Bosco-System, Ergotest Innovation, Norway).

Whole-body vibration (WBV)

A vibrating platform (Nemes-Lsb, Bosco-System, Rieti, Italy) was utilised to expose the subject to vertical sinusoidal WBV. The WBV intervention involved a rectangular protocol to find out the neuromuscular activation pattern. The subject performed seven trials at the following conditions (in random order): isometric (i.e., 0 Hz) and at 20, 25, 30, 35, 40, and 45 Hz with a 3-minute pause between each trial, lasting 30 s. The subject performed the test assuming a high squat position (elbow angle=45°, hip angle=130°, knee angle=120° and ankle angle=130°).[28] The peak-to-peak displacement for vibration stimuli was approximately 2 mm. The sEMG_{RMS} activity of VL, BF, TA, and LG was recorded during each trial (Muscle-Lab, Ergotest Innovation, Norway). The average RMS (in millivolts) was calculated for each trial (30 seconds) and it was subsequently expressed as a function of time for each muscle considered.

At the various frequencies, Co-contraction index (CI, %)[29] was determined between the extensors and flexors of the thigh muscles (VL-BF) and the extensors and flexors of the shank muscles (TA and LG). The CI was calculated considering the sEMG_{RMS} activities recorded for the entire trial's duration. The CI in the OL and the N-OL was analysed between the T0 and the T1.

Postural control

Postural control was assessed by measuring the subject's body sway while standing upright on a force platform (Muscle-Lab, Bosco-System, Ergotest Innovation, Norway). Data from the force plate was collected at a sampling frequency of 100 Hz. The subject was standing with their feet slightly extra-rotated, and their heels close together at 1.5 cm, with their arms alongside the body and their gaze fixed on a red dot at 150 cm. During the examination, the subject was positioned inside a room with walls painted white to prevent visual disturbance and to establish uniform experimental conditions. The body sway was quantified by measuring the length path of the center of pressure (COP), which represents the point of application of the resultant from the vertical force’s action. The path length of the body sway was quantified during the forward-backward (F-B) and medio-lateral (M-L) pathways with a spatial resolution of .1 - .2 mm.[30] The body sway was measured in four different conditions: bipodalic static (BPS) or bipodalic dynamic (BPD), open eyes (OE) or closed eyes (CE) (using a blindfold). All the combinations of these conditions were considered, and each trial lasted for 30 seconds. During the BPS condition, the subject was asked to stay still, while to evaluate the BPD, a pendulum system was used behind the subject to apply perturbations at predetermined intervals. These external perturbations implicated a slight imbalance every 7 seconds (7, 14; and 21 seconds) during the trial. The perturbations were directed towards the bottom portion of the subject’s shoulder blades. Throughout the OE conditions, the subject was instructed to keep a steady gaze on the red dot. The subject kept his eyes closed under a blindfold during the CE condition. Two distinct analyses were conducted to assess the BPS and BPD. Specifically, during the BPS conditions, the sway analysis encompassed the entire duration of the trial (30 seconds), identifying the F-B M-L paths. Instead, in the BPD situation, three windows were opened, and each window was 1.5 seconds long. The first marker shows how the ground reacts to external forces, and the second marker is 1.5 seconds later. The three windows during the BPD were averaged within each condition to identify a mean value for F-B, M-L.

Maximal voluntary isometric contraction (MVIC)

MVIC, synchronised with sEMG_{RMS} activity, was assessed by performing unilateral and bilateral knee extensions with an isotonic leg-extension equipped with a strain gauge (Muscle-Lab, Bosco-System, Ergotest Innovation, Norway). A maximum value of three attempts was retained for analysis. The measurement of the knee angle (120° rear) was carried out by utilising an electrogoniometer that was connected to the Muscle

Lab software (Muscle-Lab, Bosco-System, Ergotest Innovation, Norway). The subject wore a lumbar belt with the hands in grip on the lateral supports of the machine to stabilise the pelvis during the executions to minimise hip movements. Furthermore, the lever length and the sitting position were adjusted to align the joint center with the center rotation of the machine. During the MVIC, the subject was instructed to contract his leg as fast as possible, whereas the experimenter provided verbal encouragement: "push, push, push" in each trial. When the subject reached the plateau in the force-time profile monitored in real-time, the trial ended. Among the different trials, one minute of rest was observed. The quantification of the rate of force development (RFD) and maximal force value during the MVIC, both synchronised with $\mathrm{sEMG}_{\mathrm{RMS}}$, was performed in accordance with the indications reported by others.[25] A time window of 200 ms was opened for the quantification of the RFD and related $\mathrm{sEMG}_{\mathrm{RMS}}$ activity by the initial slope of the force-time profile. The maximal force and related $\mathrm{sEMG}_{\mathrm{RMS}}$ activity were measured by opening a time window of 400 ms around the peak (from -200 to +200 ms). The CI between the extensor (VL, VM, and RF) muscles and the flexor (BF) muscles was calculated[29] by taking into account the $\mathrm{sEMG}_{\mathrm{RMS}}$ activities recorded throughout the duration of the trial.

Gait analysis

Before performing gait analysis, the subject was asked to perform the 25-foot work (T25FW)[31] to identify an appropriate walking speed. As a result, a walking speed of 3.5 km/h was established, which the subject was required to maintain throughout the 30-second trial on a motorised treadmill. The SMART Motion Capture System (BTS Bioengineering, Milano, Italy), was utilised for gait analysis. The system was equipped with four optoelectronic cameras, which were strategically placed around the treadmill to perform a 3D reconstruction of the trajectories generated by reflective markers situated on the body, specifically the greater trochanter, the lateral femoral condyle, the lateral malleolus, and the fifth metatarsus. The reflective markers were placed according to the protocol reported in the literature.[32] The cameras were calibrated through a static and dynamic method that allowed us to determine the shooting volume around the treadmill. A sampling rate of 60 Hz was used to collect the data from the four optoelectronic cameras. After obtaining the recorded data, a SMART Analyser (BTS Bioengineering, Milano, Italy) was used to evaluate the trends over time of three angles (knee angle, ankle angle, and hip angle) plotted in the sagittal plane. The gait pattern in both legs was determined by hip-knee and knee-ankle diagrams.[32] The relative knee angle is formed by the extension of the thigh axis and the shank axis, the ankle angle is formed by the shank axis and foot, while the hip angle is formed by the thigh axis and the vertical hip passing through the pelvis. The angle-angle diagrams, as proposed in Cavanagh's study,[33] were generated by interpolating five identified points, namely toe off (TO), maximum knee flexion (MKF), maximum hip flexion (MHF), foot strike (FS), and maximum knee flexion during the contact phase (MKF-C). The area and the perimeters of the angle-angle were calculated using AutoCAD 2023 (Autodesk, San Rafael, CA, USA).

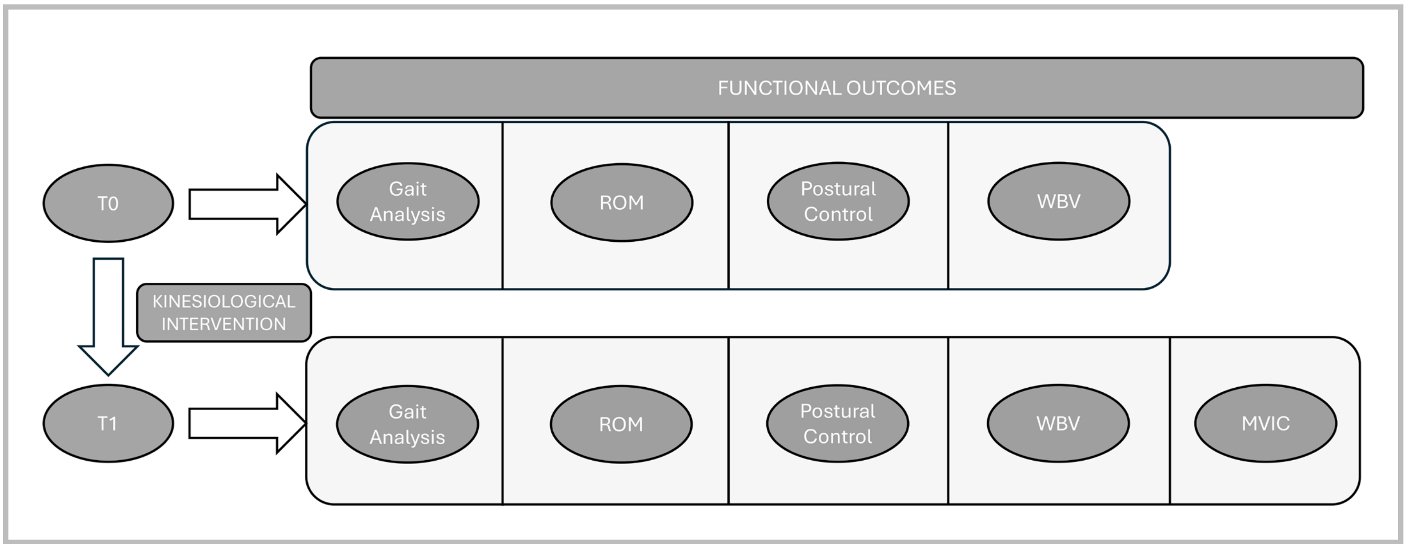

Figure 1. Timeline of the experimental design; first (T0) second assessment (T1). Surface electromyography ($\mathrm{sEMG}_{\mathrm{RMS}}$), Range of Motion (ROM), Whole-Body Vibration (WBV), Maximal Voluntary Isometric Contraction (MVIC).

Data Analysis

The CI (%) was calculated according to the following equation[29]:

$$CI\ (\%) = \frac{\sum_{i=1}^{n} \frac{lower\ EMGi}{higher\ EMGi} \times (lower\ EMGi + higher\ EMGi)}{n}$$

where *i* is the sample number and *n* is the number of data samples in the interval. A lower *EMGi* is the minimum value of the muscle activity during the task, whereas a higher *EMGi* is the maximum value. To compare the differences between T0 and T1, concerning passive ROM, gait analysis, postural control and the CI during the WBV the following formula was used:

$$\Delta\% = [\frac{(T1-T0)}{T0}] \times 100$$

The same formula was used to compare the CI between the N-OL and the OL during MVIC:

$$\Delta\% = [\frac{NOL - OL}{NOL}] \times 100$$

The $\mathrm{sEMG}_{\mathrm{RMS}}$ activity recorded for each muscle during WBV at different frequencies was compared between pre (T0) and post (T1) by using the Kolmogorov-Smirnov test. Significance was defined as $P < .05$.

Results

Range of Motion (ROM)

A flexion increases in the OL of about 18.16% and a comparable increase in the N-OL of 22.5% are revealed in the ROM assessment. Furthermore, there was an improvement of 3.23% and 4.83% respectively in the extension of the OL and N-OL.

Whole body vibration and sEMG$_{RMS}$ activity

The sEMG$_{RMS}$ activities of leg the muscles recorded during the WBV, highlighted significant differences in the OL between T0 and T1 ($P < .05$) (Fig. 2A, C). The sEMG$_{RMS}$ activities concerning the BF and the TA decreased, whereas the sEMG$_{RMS}$ of VL and LG increased. The sEMG$_{RMS}$ activities in the N-OL, did not change from T0 to T1 ($P > .05$) (Figure 2B, D). The CI showed an increase of 11.7% in the OL at 20 Hz for the thigh muscles (VL-BF), whereas the shank muscles (TA-LG) showed an increase of 112.6% at 40 Hz. On the other hand, the N-OL increased by 13.6% in the thigh muscles (VL-BF) at 30 Hz, whereas the shank muscles (TA-LG) increased by 95.7% and 140.9% respectively at 25 and 30 Hz.

Postural control

During the BPS, there was a decrease in both M-L and F-B sway path in both OE and CE conditions (Figure 3A, C). In the BPS-OE condition, the M-L sway path decreased by 48.68% and the F-B sway path decreased by 57.46%. As well as the BPS-CE condition showed a decrease in the M-L and F-B sway path 37.08% and 35.85%, respectively.

During the BPD, the M-L sway path decreased in both conditions BPD-OE and BPD-CE of 5.69% and 40.31%, respectively (Figure 3B). On the contrary, the F-B sway path showed an

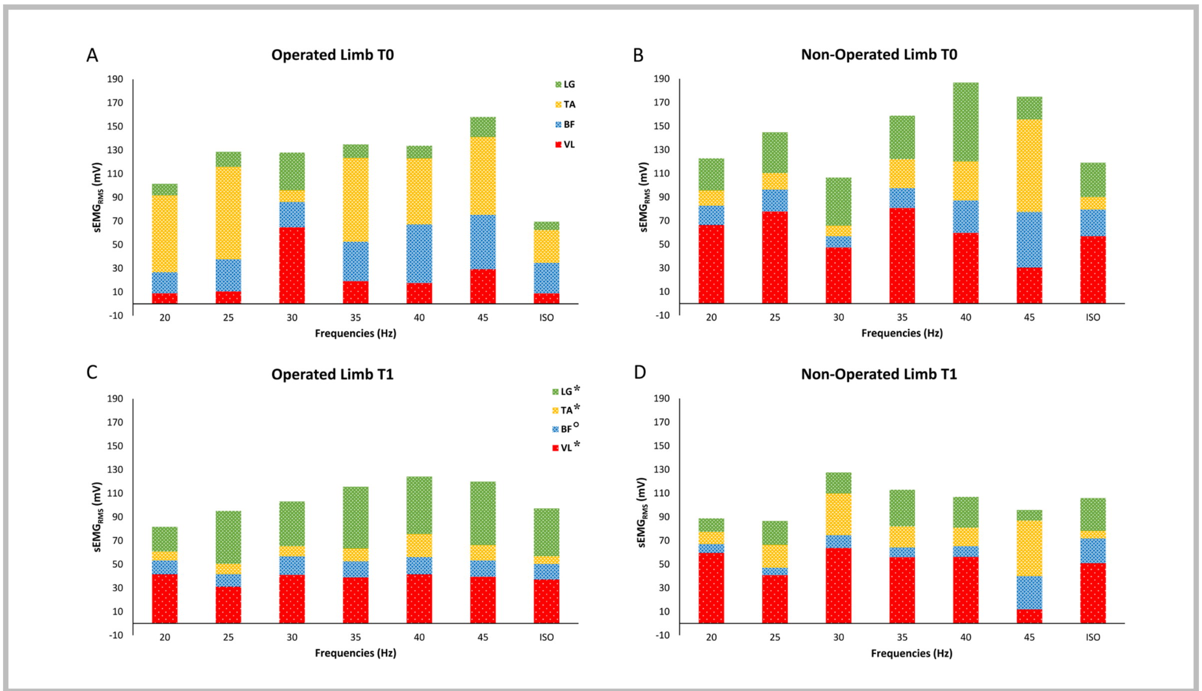

Figure 2. Neuromuscular response to different whole-body vibration frequencies. The sEMG$_{RMS}$ activity of lateral gastrocnemius (LG), tibialis anterior (TA), biceps femoris (BF), and vastus lateralis (VL). A: operated leg (OL) at T0; B: non-operated leg (N-OL) at T0; C: OL at T1; D: N-OL at T1. ISO = isometric conditions without vibrating stimulation.

° Significant differences between T0 and T1($P < .01$); * Significant differences between T0 and T1 ($P < .05$).

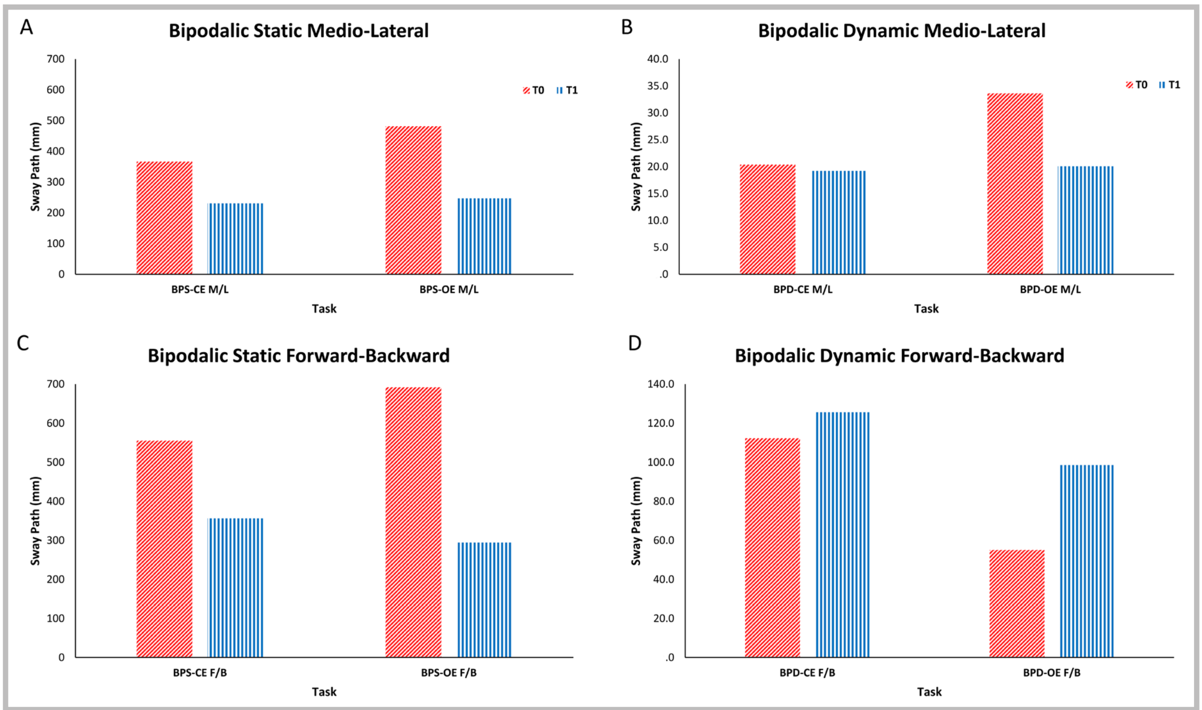

Figure 3. Body sway values in different conditions: static in medio-lateral (M/L) (A) and dynamic M/L (B), static forward-backward (F/B) (C), dynamic F/B (D); with closed (CE) and open (OE) eyes. Differences between T0 and T1 were reported.

increase in both conditions BPD-OE and BPD-CE of 11.88% and 79.06% (Figure 3D).

Maximal voluntary isometric contraction and $sEMG_{RMS}$ activity

Unilateral MVIC showed a peak force in the OL of 171.1 N and of 196.2 N in the N-OL. The Δ difference between the two limbs was equal to 12.8% (Figure 4B, C). Vice versa, the RFD was greater in the OL with a value of 251.4 N/s than in the N-OL with a value of 200.4 N/s (Δ is equal to 20%) (Figure 4B, C). The $sEMG_{RMS}$ activities showed differences between the OL and the N-OL in both conditions; the BF revealed a lower activity in the OL than in the N-OL during the bilateral (Δ= 20%) and unilateral (Δ=11%). The $sEMG_{RMS}$ of VL, VM, and RF in the OL were lower than the N-OL during unilateral exertion (Δ is equal to 41% for RF, 40% for VL and 61% for VM). Similarly, during bilateral exertion, the $sEMG_{RMS}$ of VL and VM were lower in the OL than the N-OL (Δ is equal to 36% for VL and 43% for VM) except for RF that was higher in the OL than the N-OL (Δ is equal to 25%) (Figure 4D, E, F). The differences in CI showed a greater increase in the OL than the N-OL in all the muscles considered; respectively of 37.1% for VL-BF, 57.6% for VM-BF and 32% for RF-BF.

Gait analysis

The angle-angle diagram between the hip-knee (H-K) and knee-ankle (K-A) angles showed an overlap in both the OL and N-OL at T1 compared to T0. The area showed an improvement in both limbs. There was an increase in the H-K and K-A angles for both limbs at T1. The OL increased by 24.49% in the H-K angle and 145.59% in the K-A angle. The perimeter of the OL also reported an increase of 12.32% for the H-K angle and 44.43% for the K-A angle. The N-OL improved the area of 11.25% and 54.24% for the H-K and K-A angles, respectively. Furthermore, the Δ of perimeter in the N-OL displayed an increase in the H-K and K-A angles of 4.27% and 19.38% (Figure 5A, B, C, D).

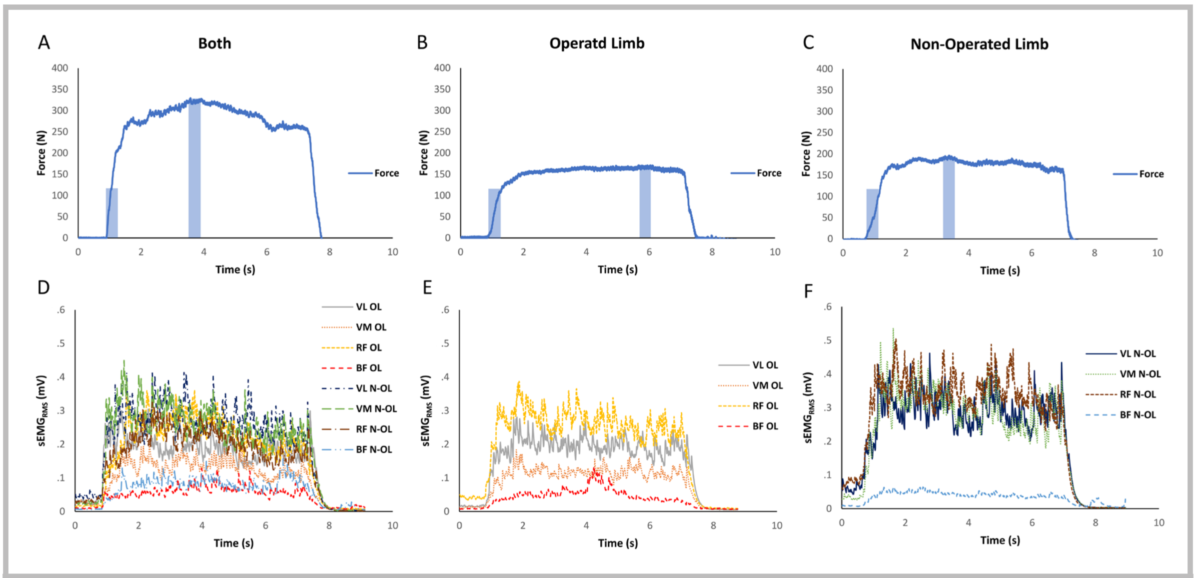

Figure 4. Force-time and $sEMG_{RMS}$-time profiles during unilateral (UL) and bilateral (BL) maximal voluntary isometric contractions (MVICs) performed at leg-extension. The synchronised $sEMG_{RMS}$ muscle activity was recorded in vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), and biceps femoris (BF). A: BL force-time; B: UL operated leg force-time; C: UL non-operated leg force-time; D: BL $sEMG_{RMS}$-time; E: UL operated leg $sEMG_{RMS}$-time; F: UL non-operated leg $sEMG_{RMS}$-time.

Discussion

The case study examined the effects of a six-month kinesiological intervention on objective functional neuromuscular, kinetic, and kinematic variables in a soccer player following patellar tendon reconstruction. Comparisons between T1 and T0 revealed improvements in the assessed variables: passive range of motion (ROM), gait analysis, postural control, and $sEMG_{RMS}$ responses to WBV. The OL exhibited an increase in knee flexion and extension by 18.18% and 3.23%, respectively. Additionally, the N-OL limb demonstrated an increase of 22.5% and 4.83% in flexion and extension, respectively. These results underscore two points: the OL and N-OL limbs had comparable ranges of motion (ROM) prior to the interventions; secondly, post-intervention, both limbs nearly regained full ROM. Vitale et al.[3] observed a steady increase in ROM over several weeks but did not assess the differences between operated and non-operated limbs. In contrast, our study focused on the final stage of management, encompassing the initial post-rehabilitation phase. Differing from Vitale et al.,[3] who only assessed the operated limb, we chose to evaluate both limbs by comparing the measurements from T0 to T1.

The ROM measurement is widely utilized to evaluate the impact of the rehabilitation phase (physiotherapy) and/or surgical intervention following a knee injury.[26] In any case, the deficits in ROM may have an impact on the subsequent kinesiological process, thereby limiting abilities such as running, sprinting, and jumping, and structuring altered patterns, such as hip and ankle compensation and knee joint function.[8] It appears that the knee joint ROM and physical exercise have a reciprocal impact,[34] since a failure to restore ROM could also negatively affect performance. In our study, ROM deficits persisted in both limbs after the rehabilitation phase, which led to the decision to include specific exercises in the kinesiological intervention to restore the function.

The WBV evaluation revealed significant differences in the OL at T1 compared to T0 in all the muscles analysed, whereas the N-OL did not exhibit significant differences. The activity of the $sEMG_{RMS}$ in the VL and LG muscles increased in the OL, on the other hand, the activity decreased in the BF and TA muscles. The

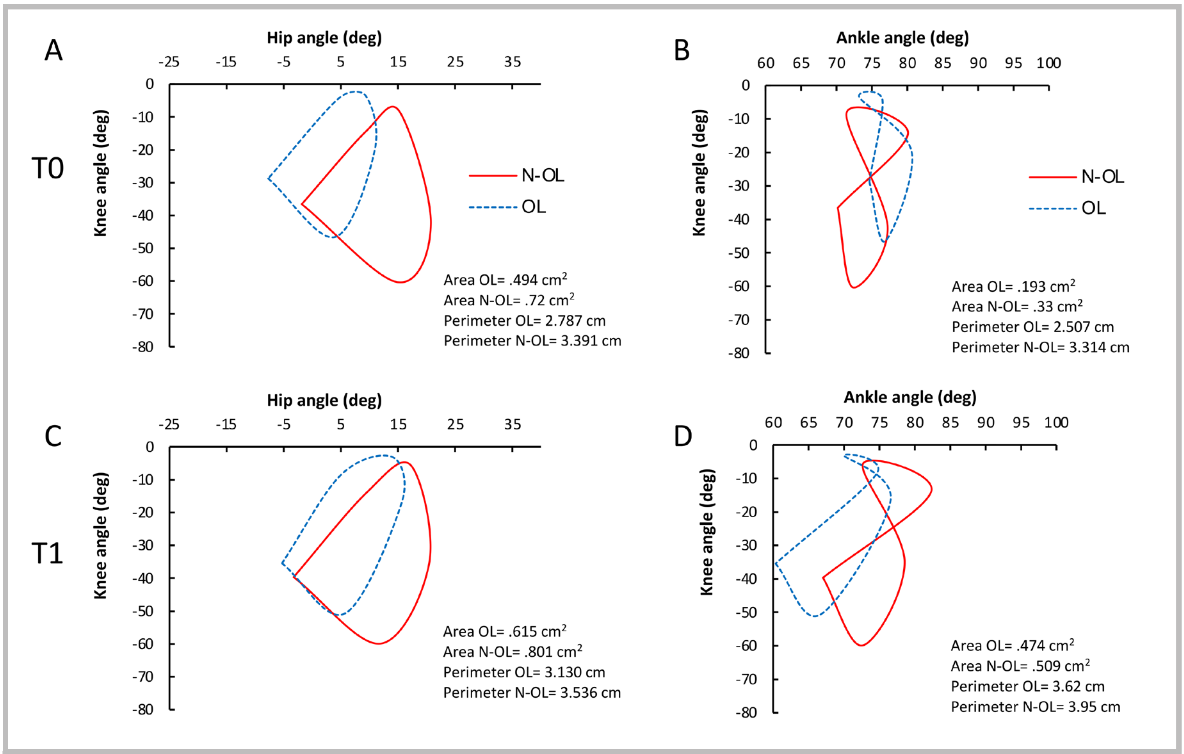

Figure 5. Angle-angle diagrams of Hip-Knee and Knee-Ankle, in the Operated Limb (OL) and Non-Operated Limb (N-OL), are reported for T0 and T1. A: Hip-Knee angles at T0; B: Knee-Ankle angles at T0; C: Hip-Knee angles at T1; D: Knee-Ankle angles at T1.

neuromuscular pattern in the OL appears like the contralateral after the kinesiological intervention. The activity increase in the LG muscle (biarticular) could contribute to knee stability with the hamstring through a knee angle lower than sixty degrees.[35,36]
The observed changes in neuromuscular activation during WBV result in CI improvements from T0 to T1. The CI, a functional parameter pertaining to joint stability,[37] increased in the thigh and shank muscles, despite the highest increase being observed between TA and LG in the OL at 40 Hz (Δ=112.6%). These neuromuscular changes revealed by WBV exposure are also consistent with the improvement in H-K and K-A diagrams (from T0 to T1) during the gait analysis. The area and perimeter of the diagrams indicate that the conjoint ROM and coordination tend to overlap more after the intervention, even though the greatest improvement was seen in the K-A diagram. As reported above, this kinematic pattern appears to be supported by muscle activation recorded during WBV, which showed a decrease in TA muscle activation and an increase in LG muscle activation. This pattern may facilitate the ankle dorsiflexion, which in turn plays a crucial role in absorbing knee loading during landing.[38] A greater ankle dorsiflexion reduces vertical ground reaction forces, thereby preserving knee stability.[38] These enhancements may be attributed to the exercises performed by the subjects on the unstable surface, both unilaterally and bilaterally, particularly during the 2° and 3° macrocycles, as reported by Nam et al.[39]
The optimisation of the activation pattern in the ankle muscles, likely induced by exercises performed with unstable surfaces in the kinesiological intervention, could also be responsible for the postural control improvements. The ability to control posture improved when standing still (BPS-OE and BPS-CE) in both the M-L and F-B sway paths. Also, during the dynamic conditions (BPD-OE and BPD-CE), an improvement in the M-L sway path was seen. Due to the lack of comparable studies, these data on postural control following patellar tendon reconstruction cannot be compared. Nonetheless, our findings can be compared with those of patellar tendinopathy, as the latter is widely recognised as a significant contributor to PTR. This is attributed to the potential degeneration of the patellar tendon structure as the tendinopathy progresses.[8] In this direction, Fendry et al.[16] have reported that subjects with patellar tendinopathy experience altered antero-posterior and medio-lateral postural control during static and dynamic conditions, compared to healthy subjects.
Following the kinesiological intervention, the subject exerted approximately equal force in both limbs, with a slightly lower value for the OL than for the N-OL (Δ=12.8%) following the MVIC. Furthermore, during unilateral MVIC, the RFD values were higher for the OL than for the N-OL during unilateral MVIC. Given that RFD is a variable that defines explosive strength, a higher value in the OL subsequent to the Kinesiological intervention could be attributed to specific adaptations in neural factors (i.e., recruitment of motor units, synchronisation of motor units).[40] During the MVIC, the $sEMG_{RMS}$ analysis showed a lesser activation of the OL, compared to the N-OL in unilateral and bilateral exertions, except for the RF. It is possible that the inhibition of the VL muscle in the OL could be due to the occurrence of an arthrogenic muscle inhibition (AMI).[41] AMI is a reflexive response in which healthy muscles are inhibited following joint injury, and it is commonly seen in the quadriceps muscles.[41] In this regard, the decrease in the $sEMG_{RMS}$ activity of the quadriceps muscle (VL, VM and RF) observed in the OL could also explain the decrease in the $sEMG_{RMS}$ activity of BF. This decrease in both agonist and antagonist muscle activity could indicate a mechanism for ensuring knee stability in the OL. The knee stability, as estimated by the CI, has not been observed between the T0 and T1, as the MVIC, being a maximal measure, was determined only at the conclusion of the kinesiological intervention. However, by comparing the OL and the N-OL during the unilateral execution, we have observed that the OL displayed a greater CI than the N-OL. As explained above, this result was due to the decrease in the extensor muscle activities (VL, VM) rather than the increase in the flexor muscle activity (BF), probably due to the AMI mechanism established following the injuries.[41] Furthermore, the AMI could explain the

slight strength difference (Δ=12.8%) between the OL and the N-OL during unilateral MVIC. In the present study, we decided to assess force during isometric muscle contraction (MVIC), rather than dynamic muscle contraction because it exerts lower stress on the patellofemoral joint.[35,42] Despite this, the isometric contraction represents a potential limitation of our investigation, as human movement and performance are characterized by power and explosive action, resulting from a combination of diverse dynamic muscle contractions, such as the stretch-shorten cycle. Anyway, during the MVIC, we have determined the RFD, which is a parameter that identifies the specific adaptations of neural factors involved in movement and power production, such as the recruitment of motor units and synchronization of motor units.

Practical Applications

The kinesiological intervention and the assessment of the different variables (gait analysis, postural control, WBV evaluation, and MVIC synchronised with $sEMG_{RMS}$) optimise the functional recovery taking in account the individual characteristics and reducing the differences between OL and N-OL. These results provide a guideline to kinesiologist in the management of the functional recovery following patellar tendon reconstruction.

Conclusions

The present study is the first case report to assess kinetic, kinematic, and neuromuscular variables following a patellar tendon reconstruction to monitor functional recovery. The functional recovery over time was monitored beginning at the end of the physiotherapy phase because all the variables were selected submaximal. The components of the kinesiological intervention, namely exercise type, quantity, and intensity, were tailored to the individual's characteristics, resulting in a reduction of the disparities between the two limbs over a period of six months. Despite this, slight differences are still present after the intervention, highlighting that additional time is necessary to restore the subject for an effective return to sport competition. The paradigm proposed, based on the stimulus-response relationship, induced specific adaptative responses for the functional recovery.

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Ethical Committee approval

University of L’Aquila Internal Review Board (IRB) approved this study (Prot. n° 33/2022).

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Conflicts of interest

The authors have no conflicts of interest to declare.

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Author-s contribution

Conceptualization, R.D.G.; methodology, S.LG., S.M., D.M.; software, S.M., D.M., S.L.G.; validation, L.R. and R.D.G.; formal analysis, S.M., S.L.G., D.M.; investigation, S.M., D.M., S.L.G.; writing—original draft preparation, D.M., S.M., S.L.G.; writing—review and editing, R.D.G.; supervision, R.D.G., L.R.; project administration, L.R. All authors have read and agreed to the published version of the manuscript.

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