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**Local vibration training improves the recovery of quadriceps strength in early rehabilitation after anterior cruciate ligament reconstruction: a feasibility randomized controlled trial**

Claire Coulondre, MSc<sup>1,2,3</sup>; Robin Souron, PhD<sup>4,5</sup>; Alexandre Rambaud, PhD<sup>4</sup>; Etienne Dalmais, MD<sup>1,2,3</sup>; Loïc Espeit, MSc<sup>4</sup>; Thomas Neri, PhD<sup>4,6</sup>; Alban Pinaroli, MD<sup>7</sup>; Gilles Estour, MD<sup>7</sup>; Guillaume Y Millet, PhD<sup>4,8</sup>; Thomas Rupp, PhD<sup>1</sup>; Léonard Feasson, PhD<sup>4,9</sup>; Pascal Edouard, PhD<sup>4,9</sup>; Thomas Lapole, PhD<sup>4</sup>

<sup>1</sup> Inter-university Laboratory of Human Movement Biology (LIBM), University of Savoie Mont Blanc, EA 7424, 73000 Chambéry, France

<sup>2</sup> Centre d'Evaluation et de Prévention ARTiculaire (CEPART), 73490 Challes-les-Eaux

<sup>3</sup> Centre d'Orthopédie et de Traumatologie du Sport, 73000 Bassens

<sup>4</sup> Univ Lyon, UJM-Saint-Etienne, Inter-university Laboratory of Human Movement Biology, EA 7424, F-42023, Saint-Etienne, France

<sup>5</sup> Laboratory of Impact of Physical Activity on Health (IAPS), UR n°201723207F, University of Toulon, France

<sup>6</sup> Department of Orthopaedic Surgery, University Hospital of Saint Etienne, Faculty of medicine, Saint-Etienne, France

<sup>7</sup> Médipôle de Savoie, 73190 Challes-les-Eaux

<sup>8</sup> Institut Universitaire de France (IUF)

<sup>9</sup> Department of Clinical and Exercise Physiology, Sports Medicine and Myology Units, Regional Institute of Medicine and Sports Engineering (IRMIS), University Hospital of Saint-Etienne, Faculty of medicine, Saint-Etienne, France

Running title: Local vibration in ACL rehabilitation

Corresponding author:

Thomas LAPOLE

Laboratoire Interuniversitaire de Biologie de la Motricité

Bâtiment IRMIS

10 rue de la Marandière

42270 Saint Priest en Jarez

04 77 42 18 91; [thomas.lapole@univ-st-etienne.fr](mailto:thomas.lapole@univ-st-etienne.fr)

275 **Local vibration training improves the recovery of quadriceps strength in early**  
276 **rehabilitation after anterior cruciate ligament reconstruction: a feasibility randomized**  
277 **controlled trial**

278

279 **ABSTRACT**

280 **Background.** After anterior cruciate ligament reconstruction (ACLR), quadriceps strength  
281 must be maximized as early as possible.

282 **Objectives.** We tested whether local vibration training (LVT) during the early post-ACLR  
283 period (i.e., ~10 weeks) could improve strength recovery.

284 **Methods.** This was a multicentric, open, parallel-group, randomized controlled trial. Thirty  
285 individuals attending ACLR were randomized by use of a dedicated Web application to 2  
286 groups: vibration (standardized rehabilitation plus LVT, n=16) or control (standardized  
287 rehabilitation alone, n=14). Experimenters, physiotherapists and participants were not blinded.  
288 Both groups received 24 sessions of standardized rehabilitation over ~10 weeks. In addition,  
289 the vibration group received 1 hr of vibration applied to the relaxed quadriceps of the injured  
290 leg at the end of each rehabilitation session. The primary outcome — maximal isometric  
291 strength of both injured and non-injured legs (i.e., allowing for limb asymmetry measurement)  
292 — was evaluated before ACLR (PRE) and after the 10-week rehabilitation (POST).

293 **Results.** Seven participants were lost to follow-up, so data for 23 participants were used in the  
294 complete-case analysis. For the injured leg, the mean (SD) decrease in maximal strength from  
295 PRE to POST was significantly lower for the vibration than control group (n=11, -16% [10] vs  
296 n=12, -30% [11]; p=0.0045, Cohen's d effect size = 1.33). Mean PRE-POST change in limb  
297 symmetry was lower for the vibration than control group (-19% [11] vs -29% [13]) but not  
298 significantly (p=0.051, Cohen's d effect size = 0.85).

299 **Conclusion.** LVT improved strength recovery after ACLR. This feasibility study suggests that  
300 LVT applied to relaxed muscles is a promising modality of vibration therapy that could be  
301 implemented early in ACLR.

302

303 **Trial registration.** ClinicalTrials.gov: NCT02929004

304

305 **Keywords:** local vibration; strength; rehabilitation; anterior cruciate ligament reconstruction

306

307

## 308 **Introduction**

309 After anterior cruciate ligament reconstruction (ACLR), the ultimate goal of rehabilitation is to  
310 restore function of the lower limbs to pre-injury levels [1]. However, patients present large  
311 quadriceps strength deficits in the first weeks after ACLR [2, 3]. For instance, limb asymmetry  
312 (i.e., difference in maximal isometric strength between the injured and non-injured leg) has  
313 been reported as 36% and 19% at 5 and 12 weeks after ACLR, before returning to the pre-  
314 surgery level 26 weeks after ACLR [3]. Quadriceps weakness may even persist up to 2 years  
315 after ACLR [2]. This weakness may increase both the delay and quality of a return to sport/play  
316 [4] and risk of second ipsi- or contralateral ACL injury [5]. It may also contribute to patella-  
317 femoral pain [6], altered gait pattern [7] and running biomechanics [8], which altogether impair  
318 the rehabilitation process and prevent a return to work as well as sports. The risk of developing  
319 knee joint osteoarthritis is increased owing to quadriceps strength loss [9]. Therefore,  
320 quadriceps strength should be maximized as early as possible after ACLR [10].

321 Quadriceps weakness after ACLR can be explained in part by muscle wasting [11], but  
322 quadriceps activation failure also substantially contributes to the functional impairment [2, 12].  
323 Quadriceps activation failure refers to the inability to fully recruit motor units and/or at a  
324 sufficient discharge rate, mainly because of altered corticospinal excitability [12, 13] and/or

325 arthrogenic muscle inhibition, defined as neural inhibition arising from alterations in spinal  
326 reflex pathways due to factors such as swelling and inflammation [14]. Therefore, reactivating  
327 quadriceps is the first aim of early rehabilitation [1]. However, the immediate post-surgery  
328 context (e.g., graft healing, pain, meniscal sutures) prevents the optimal use of strength training.  
329 Hence, practical guidelines currently recommend quadriceps isometric exercises during the first  
330 week post-surgery, associated or not with cryotherapy to reduce pain and arthrogenic muscle  
331 inhibition [1]. In the following weeks, neuromuscular electrostimulation is also recommended  
332 [1, 15]. When quadriceps are reactivated and when graft healing and potential complications  
333 no longer exist, neuromuscular training and strength exercises can be implemented to further  
334 strengthen the quadriceps [1]. These guidelines clearly emphasize the need to enhance  
335 quadriceps neural drive as soon and as efficiently as possible after surgery, despite the  
336 aforementioned post-surgery issues.

337         In the last decade, vibration therapy has gained popularity. It consists in delivering  
338 vibration using whole-body vibration (WBV) platforms [16, 17] or directly to muscles or  
339 tendons by using local vibration (LV) [18]. In the context of ACLR, a single session of WBV  
340 or LV while patients maintain a squat position has been reported to acutely improve quadriceps  
341 strength when applied 50 months post-surgery, likely by reducing arthrogenic muscle inhibition  
342 [19]. However, similar results were not observed when WBV was applied at a mean of 17 weeks  
343 post-ACLR [20]. Moreover, when applied chronically as a training intervention, several weeks  
344 of WBV improved muscle strength when the intervention was started at least 1 month after  
345 ACLR but not during the second week of rehabilitation [17]. Three consecutive days of LV  
346 applied to isometrically contracted quadriceps 1 month after surgery also improved quadriceps  
347 strength when evaluated 9 months later [21].

348         Although the aforementioned studies provided promising results for ACLR  
349 rehabilitation, they may not be applicable in the early period after ACLR when the quadriceps

350 is not yet reactivated [1]. An alternative could be to apply LV directly over the relaxed  
351 quadriceps by using a small and portable device [18]. When using appropriate LV  
352 characteristics (e.g., frequency or amplitude), repetitive small changes in muscle length  
353 strongly activate afferents originating from muscle spindles (i.e., mechanoreceptors sensitive  
354 to muscle stretch [22]), projecting their excitatory synaptic inputs to the spinal cord and cortical  
355 areas [18]. As a result, prolonged LV exposure at rest (i.e., 20 to 60 min) has been found to  
356 induce acute neural modulations in healthy individuals [18, 23, 24]. When chronically used  
357 (i.e., LV training [LVT]), prolonged LV exposure can in turn trigger long-term adaptations  
358 [18]. Accordingly, we recently demonstrated that 4 weeks of LVT applied over the relaxed  
359 quadriceps significantly increased muscle strength in healthy individuals, and the improved  
360 neural drive mainly accounted for the gains [25]. These results, combined with the simplicity  
361 (a key parameter in clinical settings) of using LVT [18], suggest that this technique may be  
362 promising in terms of promoting neuromuscular reconditioning during the early rehabilitation  
363 period after ACLR.

364         This study aimed to test whether adding LVT to standardized rehabilitation during the  
365 early post-ACLR period (i.e., ~10 weeks) could improve quadriceps strength recovery as  
366 compared with standardized rehabilitation alone.

367

## 368 **Materials and methods**

### 369 *Study design*

370 This was a multicentric, open, parallel-group, randomized controlled trial including individuals  
371 who underwent ACLR between December 2016 and January 2020. This study conformed to  
372 standards from the latest revision of the Declaration of Helsinki and was approved by the  
373 Committee for the Protection of Persons (CPP Sud-est I, no.: 2016-34). The University Hospital  
374 of Saint-Etienne (France) was the sponsor of this study (ClinicalTrials.gov: NCT02929004).

375

376 ***Population and procedure***

377 Eligible participants were 18 to 50 years old, had unilateral ACL tear and were awaiting surgery  
378 for unilateral ACLR (with hamstring or patellar tendon autograft). They were identified from  
379 contacts with 5 primary (i.e., physiotherapy clinics) and 4 tertiary (i.e., orthopedic departments)  
380 healthcare centres of our network in Saint-Etienne and Chambéry, France. Exclusion criteria  
381 were previous ACLR, taking neuro-active substances, acute or chronic neurological disorders,  
382 or being a professional athlete.

383 Participants first visited the laboratory within 15 days before surgery for an initial  
384 inclusion dedicated to the assessment for eligibility, medical checking, provision of written  
385 informed consent, and familiarization with the experimental procedures before performing  
386 baseline measurements (PRE).

387 Immediately after surgery and before the beginning of rehabilitation, we used the  
388 REDCap Web application (<https://redcap-ex.chu-st-etienne.fr/redcap/>) to randomly assign  
389 participants to the control (i.e., standard rehabilitation) or vibration group (i.e., standardized  
390 rehabilitation plus LVT). Experimenters, physiotherapists and participants were not blinded.  
391 Participants had to attend a second visit to the laboratory after 24 sessions of rehabilitation  
392 performed within 8 to 11 weeks (depending on schedule possibilities) post-surgery (POST).  
393 Figure 1 illustrates the flow of participants in the study.

394

395 ***Standard rehabilitation protocol***

396 Both groups performed a standardized post-ACLR rehabilitation. Each participant was  
397 supervised by their own physiotherapist who agreed to apply the protocol that had previously  
398 been sent. The rehabilitation protocol used was similar to the one presented in S1 Appendix of  
399 [26]. Briefly, participants had to follow 2 to 3 rehabilitation sessions per week, with at least 1



400 day of rest in between, for a total of 24 sessions within 8 to 11 weeks of rehabilitation. In the  
401 first phase, rehabilitation focused on early motion and basic movement retraining (e.g.,  
402 achieving full knee extension, minimizing swelling, regaining quadriceps activity and control).  
403 The second phase began approximately 3 weeks after surgery (i.e., when patients presented a  
404 closed wound, minimal effusion, knee extension close to 0° and flexion close to 90°, normal  
405 mobility of the patellofemoral joint, and reactivated quadriceps). This phase was dedicated to  
406 basic strength and proprioception (e.g., restoring proper body alignment and control, building  
407 lower extremity and core body strength, improving proprioception).

408

#### 409 ***Intervention: local vibration***

410 In addition to the standardized rehabilitation, the vibration group performed the vibration  
411 program, which consisted of 1-hr vibration sessions at the end of each rehabilitation session to  
412 avoid any potential influence of vibration-induced fatigue on the rehabilitation protocol [24].  
413 The vibrating device (VB 115, Techno Concept, Mane, France) was applied locally and  
414 strapped with elastic Velcro fasteners directly on the rectus femoris muscle (i.e., 40% of the  
415 muscle length from the upper edge of the patella to the anterior superior iliac spine) of the  
416 injured leg [25] (Fig. 2). The participant was seated on a chair during the entire vibration  
417 session, with a knee angle as close as possible to 90°. Considering that small vibration  
418 amplitudes and frequencies up to 80 to 120 Hz are highly effective for stimulating muscle  
419 spindle afferents [18], vibration characteristics were set at 100-Hz frequency and 1-mm  
420 amplitude as in our previous studies [25, 27].

421

#### 422 ***Primary and secondary outcomes***

423 PRE and POST measurements consisted of strength and functional measurements. Participants  
424 were instructed to avoid the consumption of caffeine on the day of the experiment and avoid

425 performing any strenuous exercise for 48 hr before testing. Strength measurements were first  
426 performed on the non-injured, then injured leg. Participants were seated upright in a custom-  
427 built chair with both knee and hips at 90° flexion. Knee extensor isometric strength was  
428 assessed by using a calibrated force transducer (Omega Engineering, Stamford, CT), which was  
429 attached above the participant's malleoli. During contraction, participants were instructed to  
430 pull against the strain gauge (i.e., knee extension) and were provided with real-time feedback  
431 of their strength on a screen. Movements of the upper body were minimized by using belts  
432 across the thorax and waist. After a standardized warm-up consisting of 10 isometric  
433 contractions of the knee extensors at increasing intensities until reaching 90% of the perceived  
434 maximal strength followed by a 3-min rest, participants were asked to perform two 5-sec  
435 maximal voluntary contractions (MVCs) separated by 60 sec of rest. If the difference between  
436 the two MVCs was > 5%, participants performed a third MVC. During MVCs, participants  
437 were instructed to extend their knee (in isometric condition) "as hard as possible" and were  
438 verbally encouraged.

439         After a 3-min rest, participants performed a series of 5 explosive isometric contractions  
440 (~0.5 sec) separated by 30 sec of rest to determine the rate of force development (RFD).  
441 Participants were instructed to isometrically extend their knee "as fast as possible," and strong  
442 verbal encouragement was provided. The trial was repeated again if 1) countermovement was  
443 detected (i.e., a quick flexion before the knee extension was determined from a force drop of 2  
444 N below the baseline) or 2) the force reached < 70% of the maximal strength previously  
445 recorded [28].

446         The primary outcome of the study was the maximal isometric strength defined as the  
447 highest strength occurring during 500 ms. The limb symmetry index (LSI) was calculated to  
448 compare quadriceps maximal isometric strength between the injured and non-injured leg (i.e.,  
449  $LSI_{Strength}$ ):

450 
$$LSI (\%) = \left( \frac{\text{injured leg}}{\text{non - injured leg}} \right) \times 100$$

451 The secondary outcome was the RFD, defined as the average slope over 100 ms ( $\Delta\text{force}/\Delta\text{time}$ ,  
452 Nm/s) [29] from the onset of the contraction. The onset of the force development was defined  
453 automatically as the point at which force exceeded 3 SDs over the average resting baseline [30].  
454 The mean of the 5 impulsive contractions was retained for analysis. LSI was also calculated for  
455 RFD (i.e.,  $LSI_{\text{RFD}}$ ).

456 Functional performance was also measured as a secondary outcome and included the  
457 Timed Up and Go test (TUG) and the Six-Minute Walk Test (6MWT). We initially aimed to  
458 investigate the level of voluntary activation by using transcranial magnetic stimulation during  
459 MVC [25], but as another secondary outcome, this test was finally not included owing to the  
460 inability of our second recruiting centre to perform such testing.

461

#### 462 ***Sample size calculation***

463 As the primary outcome of the present study, quadriceps strength was used for sample size  
464 calculation with G\*Power v3.1. Considering one of our recent studies that investigated the  
465 effect of LVT on dorsiflexion isometric maximal strength of healthy individuals [27], a  
466 between-group effect size of 1.09 for PRE–POST changes in quadriceps strength was expected  
467 and initially used for calculating the required sample size. The calculated sample size was 38  
468 (i.e., 19 per group) to achieve a power of 0.90 at an alpha level of 0.05. Because of a  
469 disappointing recruitment rate, we revised the sample size calculation by considering a more  
470 recent study that investigated the effect of LVT on quadriceps strength of healthy individuals.  
471 The calculated sample size was 22 (i.e., 11 per group) based on an effect size of 1.3 with a  
472 power of 0.80 at an alpha level of 0.05. Considering a potential 30% withdrawal, we included  
473 30 individuals.

474

475 ***Statistical analysis***

476 Data are presented as mean  $\pm$  standard deviation (SD) for continuous variables and number (%)  
477 for categorical variables. Statistical tests were performed with Statistica (StatSoft Inc., Tulsa,  
478 OK). All variables were normally distributed (Kolmogorov-Smirnov normality test). For  
479 ANCOVA analyses, homogeneity of variance was verified by the Levene test.  $P < 0.05$  was  
480 considered statistically significant. The comparability of between-group characteristics was  
481 tested by unpaired Student *t* test for continuous variables and chi-square test for categorical  
482 variables. Complete-case analyses were used for both primary and secondary outcomes.

483 To analyse maximal isometric strength and RFD values, a mixed model ANCOVA was  
484 used with “leg” (non-injured vs injured) and “time” (PRE vs POST) as within-subject variables,  
485 group (control vs vibration) as a between-subject variable, and baseline scores (i.e., PRE values)  
486 as covariates. For LSI and functional measurements, a mixed model ANCOVA was used with  
487 “time” (PRE vs POST) as a within-subject variable, “group” (control vs vibration) as a between-  
488 subject variable, and PRE values as covariates. Post-hoc analyses were performed with  
489 Bonferroni testing when ANCOVAs identified significant differences. Estimated effect size  
490 was reported as partial eta square ( $\eta^2$ ) (with  $\eta^2 \geq 0.07$  and  $\geq 0.14$  used as moderate and large  
491 effects, respectively [31]).

492 Moreover, besides ANCOVAs performed on raw values, we further calculated for each  
493 parameter the mean PRE–POST changes with 95% confidence intervals to compare the  
494 magnitude of recovery between groups by using ANCOVA (with “group” as a between-subject  
495 variable and baseline scores as covariates):

496 
$$PRE - POST \text{ change } (\%) = \left( \frac{POST - PRE}{PRE} \right) \times 100$$

497 For PRE–POST changes, Cohen’s *d* effect size with 95% confidence intervals were calculated  
498 (with values of  $d = 0.2$ ,  $0.5$  and  $0.8$  considered small, medium and large effects, respectively)  
499 [31].

500

## 501 **Results**

502 Among 30 participants initially included in the study, 7 were lost to follow-up, so 23 were  
503 included in the complete-case analysis: 12 randomly assigned to the control group and 11 to  
504 the vibration group (Fig. 1 and Table 1). No adverse effects of the vibration program were  
505 reported.

506

### 507 *Primary outcome*

508 We found a significant leg  $\times$  time  $\times$  group interaction for maximal strength ( $F_{(1,19)}=4.56$ ;  
509  $p=0.046$ ;  $\eta^2=0.19$ ). PRE and POST values did not differ for the non-injured leg for both the  
510 vibration ( $p=1$ ) and control ( $p=1$ ) groups, but values for the injured leg were significantly  
511 decreased from PRE to POST for the vibration ( $p=0.009$ ) and control ( $p<0.001$ ) groups (Table  
512 2). Mean PRE–POST changes (Fig. 3A) did not differ between groups for the non-injured leg  
513 ( $p=0.37$ ) but were significantly lower for the vibration than control group for the injured leg  
514 ( $p=0.0049$ ).

515 When considering  $LSI_{Strength}$ , we found a significant interaction between group and time  
516 ( $F_{(1,20)}=5.74$ ;  $p=0.026$ ;  $\eta^2=0.22$ ).  $LSI_{Strength}$  was significantly decreased from PRE to POST for  
517 both the vibration ( $p<0.001$ ) and control groups ( $p<0.001$ ). The between-group difference in  
518 mean PRE-POST changes were not significant ( $p=0.051$ ; Fig. 4A).

519

### 520 **Secondary outcomes**

521 RFD for 1 participant of the control group was not recorded because of the inability of the  
522 person to avoid countermovement before explosive knee contractions (i.e.,  $n=11$  in both groups  
523 for this parameter). We found no leg  $\times$  time interaction ( $F_{(1,18)}=1.67$ ;  $p=0.21$ ;  $\eta^2=0.085$ ) nor  
524 further interaction with the group factor ( $F_{(1,18)}=3.33$ ;  $p=0.085$ ;  $\eta^2=0.16$ ) (Table 2).

525 Accordingly, the vibration and control groups did not significantly differ in mean changes in  
526 RFD for the non-injured leg ( $p=0.32$ ; Fig. 3B) or the injured leg ( $p=0.10$ ; Fig. 3B).  
527 We found a significant group  $\times$  time interaction for  $LSI_{RFD}$  ( $F_{(1,19)}=4.42$ ;  $p=0.049$ ;  $\eta^2=0.19$ ).  
528  $LSI_{RFD}$  was significantly decreased from PRE to POST in the control group ( $p<0.001$ ) but not  
529 vibration group ( $p=0.13$ ). The groups did not significantly differ in mean PRE-POST  $LSI_{RFD}$   
530 changes ( $p=0.095$ ; Fig. 4B).  
531 Regarding functional measures (Table 2), we found no significant time ( $F_{(1,19)}=1.33$ ;  $p=0.26$ ;  
532  $\eta^2=0.19$ ) or group  $\times$  time interaction ( $F_{(1,19)}=0.77$ ;  $p=0.39$ ;  $\eta^2=0.13$ ) for TUG performance,  
533 nor time ( $F_{(1,19)}=0.037$ ;  $p=0.85$ ;  $\eta^2=0.054$ ) or group  $\times$  time interaction ( $F_{(1,19)}=0.89$ ;  $p=0.36$ ;  
534  $\eta^2=0.15$ ) for 6MWT performance. The groups did not significantly differ in mean PRE-POST  
535 changes in the TUG and 6MWT ( $p=0.37$  and  $0.36$ , respectively).

536

## 537 **Discussion**

538 To the best of our knowledge, this was the first study to examine the effect of LVT on  
539 quadriceps strength during early ACLR rehabilitation. The main finding of this randomized  
540 controlled trial was that adding LVT to a standardized rehabilitation early (~10 weeks) after  
541 surgery improved the strength recovery of the injured leg. This observation was evidenced by  
542 the significant attenuation of maximal isometric strength reduction from PRE to POST (primary  
543 outcome) in the vibration versus control group. However, the groups did not differ in recovery  
544 of RFD or TUG and 6MWT performance (secondary outcomes).

545 Individuals with ACLR are well known to experience quadriceps muscle weakness in  
546 the injured leg after surgery [2]. Accordingly, we observed a residual decrease in maximal  
547 isometric quadriceps strength in the present study ~10 weeks after ACLR, which was associated  
548 with an increased inter-limb asymmetry (i.e., decreased  $LSI_{Strength}$ ). Thus, reduced strength  
549 capacities can be attributed to alterations within the quadriceps muscle (i.e., muscle atrophy

550 and alteration in contractile function [11]), and/or voluntary activation failure (i.e., reduced  
551 neural drive via diminished excitability of spinal-reflexive and/or corticospinal pathways [2,  
552 12]). Cross-sectional studies reported altered explosive contraction capacities in individuals  
553 several months after ACLR as compared with controls [32], but we did not find any conclusive  
554 difference in RFD between PRE and POST measurements.

555 Our results show that adding LVT to the standardized rehabilitation attenuated the  
556 reduced strength capacity. Indeed, the participants who followed the LVT lost almost twice as  
557 less (-16 vs -30%; large effect size) maximal isometric strength of their injured leg than their  
558 counterparts who did not use LVT. Despite the large effect size, there was no significant effect  
559 on LSI ( $p=0.051$ ; see below). Nonetheless, this observation agrees with previous findings  
560 showing force improvement in healthy individuals after a training intervention with similar  
561 vibration characteristics [25, 27, 33-35]. Specifically, for the quadriceps muscles, LVT was  
562 reported to induce a 14% strength increase in postmenopausal women after 26 weeks of training  
563 with 5 sessions per week [35] or a 12% gain after 12 sessions over 4 weeks [25]. After 4 and  
564 12 weeks of LVT, quadriceps maximal strength increased by 30% in healthy individuals [36]  
565 and 63% in those with sarcopenia [37], respectively. However, these 2 studies, contrary to the  
566 previous cited LVT studies, did not include a control condition, which prevents from conclusive  
567 interpretation of their results. Altogether, growing evidence suggests that LVT may improve  
568 strength capacity, and the present study supports this concept in the context of early ACLR  
569 rehabilitation. However, the effect of LVT on RFD is less clear. RFD was not altered from PRE  
570 to POST, but  $LSI_{RFD}$  was significantly reduced in the control group only, without any group  
571 difference in PRE–POST changes.

572 The main strength of the study is showing the effectiveness of LVT to improve strength  
573 recovery in the early rehabilitation phase after ACLR. Although it would have been interesting  
574 to report indicators of self-reported function, the included sample was relevant because it well

575 represented the average population that physiotherapists have to supervise during post-ACLR  
576 rehabilitation [38]. The primary outcome was meaningful and relevant in clinical practice. For  
577 instance, minimizing quadriceps strength loss during the first months post-ACLR can predict  
578 improved running biomechanics [39]. Yet, we found no functional changes when considering  
579 TUG and 6MWT performance, but these tests are not sensitive in the context of ACLR (i.e., no  
580 changes were observed in the control group).

581         Our study involved a relatively small sample size, lower than the initial sample size  
582 reported in ClinicalTrials.gov. Although we report a between-group effect size of 1.33 for PRE–  
583 POST changes in quadriceps strength of the injured leg, reaching an *a posteriori* power of 0.86,  
584 this may have prevented some results to be significant (e.g., LSI<sub>strength</sub>). Including more  
585 participants would have better revealed surgery-induced alterations in RFD as well as the  
586 potential effects of LVT. Studies with larger sample sizes are also needed to allow for  
587 generalisation (e.g., by considering graft type and/or sex as covariates in the analyses). Another  
588 limitation of the present study may be the lack of blinding, and further studies should try to  
589 propose a control sham condition. Finally, our experimental design did not allow for  
590 determining the exact mechanisms involved in the LVT-induced preservation in strength  
591 capacities, and one can only be speculative. Because neural adaptations were proposed as the  
592 main explanation for strength gains after LVT in healthy individuals [18], further investigations  
593 are needed to determine whether adding LVT to standardized rehabilitation can prevent the  
594 deleterious effects that arthrogenic muscle inhibition [14] and/or altered corticospinal  
595 excitability [12, 13] may have on neural drive after ACLR. Potential effects of LVT on muscle  
596 atrophy also need to be considered [40].

597



598 **Conclusions**

599 The present study reports that LVT can improve strength recovery after ACLR. Importantly,  
600 no adverse effects were reported, so this technique can provide a high risk/benefit ratio in that  
601 it requests no help from a clinician and can even be used as a self-rehabilitation technique at  
602 home. Despite some limitations and that the study can be considered only a feasibility study,  
603 the present results suggest that LVT on relaxed muscles is a promising modality of vibration  
604 therapy and could be implemented in the early period of ACLR rehabilitation in addition to  
605 standardized rehabilitation.

606

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609 device.

610

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614

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617

618 **Legends**

619 **Fig. 1.** Flow of participants in the study (Consolidated Standards of Reporting Trials  
620 [CONSORT]).

621 **Fig. 2.** The vibrating device used for local vibration training.

622 **Fig. 3.** Mean and individual PRE–POST changes in maximal isometric strength (A) and rate of  
623 force development (RFD) (B) for the non-injured and injured legs for control and vibration  
624 groups. Data are mean (SD). \* P<0.05. PRE, before anterior cruciate ligament reconstruction;  
625 POST, and after 10-week rehabilitation.

626 **Fig. 4.** Mean and individual PRE–POST changes in limb symmetry index for strength  
627 (LSI<sub>Strength</sub>) (A) and LSI for rate of force development (LSI<sub>RFD</sub>) (B) for control and vibration  
628 groups. Data are mean (SD). PRE, before anterior cruciate ligament reconstruction; POST, and  
629 after 10-week rehabilitation.

630

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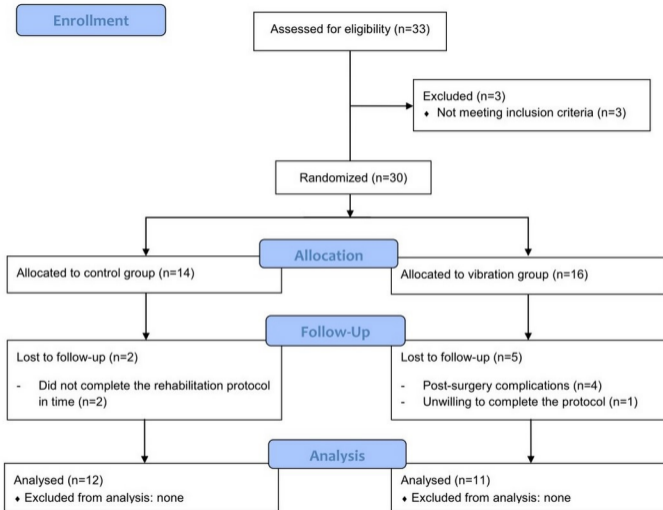
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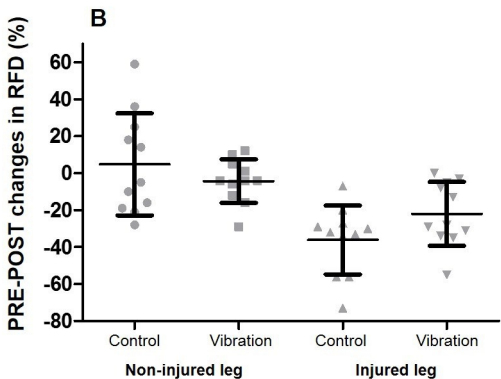
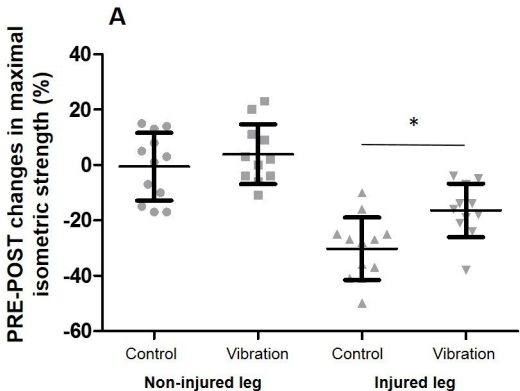
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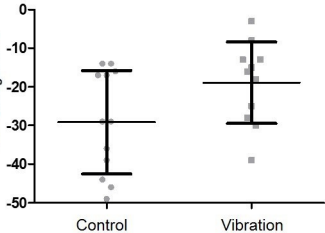






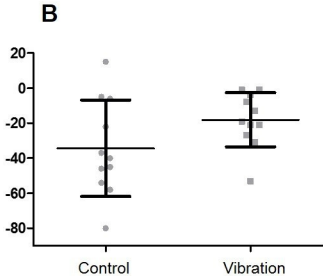
**PRE-POST changes in**

**LSI<sub>strength</sub> (%)**



**PRE-POST changes in**

**LSI<sub>RFD</sub> (%)**



275 Table 1. Characteristics of participant groups.

	Control group (n=12)	Vibration group (n=11)	<i>P</i> -value (Group effect)
Age (years)	29 (9)	30 (10)	0.86
Sex (male / female)	7 / 5	6 / 5	0.86
Mass (kg)	75 (18)	74 (20)	0.88
Height (cm)	176 (12)	172 (9)	0.37
Body mass index (kg/m <sup>2</sup> )	23.7 (3)	24.7 (6)	0.64
Pre-injury activity physical activity level (Tegner)	7.4 (1.9)	6.7 (2.3)	0.44
Leg dominance (left / right)	1 / 11	2 / 9	0.48
Injured leg (left / right)	4 / 8	4 / 7	0.88
Graft type (hamstring tendon / bone-patellar tendon-bone)	9 / 3	10 / 1	0.32
Concomitant meniscal repair	5	3	0.26

Concomitant anterolateral ligament reconstruction	5	4	0.41
Time between pre-tests and surgery (days)	5.4 (3.9)	4.4 (3.1)	0.48
Time between surgery and post-tests (days)	70.6 (6.4)	74.0 (5.5)	0.19

276 Data are mean (SD) or number.

Table 2. Maximal isometric strength, rate of force development (RFD), limb symmetry index (LSI) and functional performance [Timed Get Up and Go test (TUG) and Six-Minute Walk Test (6MWT)] for control and vibration groups before surgery (PRE) and after the intervention (POST).

	Control group		Vibration group		Effect size (Cohen's d [95% CI])		
	PRE	POST	PRE	POST	PRE to POST Control	PRE to POST Vibration	Difference in recovery between groups
	<b>Maximal isometric strength (N)</b>						
Non-injured leg	712 (215)	706 (240)	616 (219)	629 (197)	0.03 [-0.20 to 0.26]	0.06 [-0.12 to 0.24]	0.38 [-0.44 to 1.21]
Injured leg	567 (216)	398 (160)*	555 (230)	468 (219)*	0.89 [0.44 to 1.33]	0.39 [0.16 to 0.61]	1.33 [0.43 to 2.24]
LSI <sub>Strength</sub> (%)	80 (18)	56 (15)*	90 (16)	72 (12)*	1.42 [0.67 to 2.14]	1.26 [0.50 to 1.98]	0.85 [-0.0035 to 1.71]
<b>RFD (N/s)</b>							
Non-injured leg	3060 (1087)	3113 (1255)	3083 (1129)	3060 (1087)	0.05 [-0.32 to 0.41]	0.15 [-0.03 to 0.33]	0.43 [-0.41 to 1.28]
Injured leg	2522 (906)	1659 (867)	2799 (1172)	2522 (906)	0.97 [0.46 to 1.47]	0.48 [0.16 to 0.79]	0.79 [-0.073 to 1.66]
LSI <sub>RFD</sub> (%)	85 (22)	54 (23)*	90 (11)	85 (22)	1.40 [0.39 to 2.36]	0.96 [0.35 to 1.56]	0.73 [-0.13 to 1.59]
<b>Functional measures</b>							
TUG (s)	6.98 (0.77)	7.54 (0.88)	6.92 (1.46)	7.24 (1.52)	0.67 [0.04 to 1.28]	0.21 [-0.01 to 0.43]	0.39 [-0.46 to 1.23]
6MWT (m)	590 (71)	570 (69)	547 (89)	551 (109)	0.29 [-0.11 to 0.36]	0.03 [-0.30 to 0.36]	0.40 [-0.45 to 1.24]

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Data are mean (SD) unless indicated.

\* indicates significantly different from PRE