Acta of Bioengineering and Biomechanics
Vol. 17, No. 2, 2015

Original paper
DOI: 10.5277/ABB-00208-2014-04

Biomechanical characteristics of the jump down of healthy subjects and patients with knee injuries

ALEKSANDRA MELIŃSKA[1]*, ANDRZEJ CZAMARA[2], ŁUKASZ SZUBA[2], ROMUALD BĘDZIŃSKI[3]

[1] Wrocław University of Technology, Institute of Biomedical Engineering and Instrumentation, Wrocław, Poland.
[2] College of Physiotherapy in Wrocław, Wrocław, Poland.
[3] University of Zielona Góra, Faculty of Mechanical Engineering, Biomedical Engineering Group, Zielona Góra, Poland.

Purpose: The aim of this study is to investigate the drop jump performance of male patients who underwent ACLR and a control group using combined data acquisition system. Methods: A total of 28 male subjects aged 20 to 26 were studied: 22 did not show and were not diagnosed with any knee joint dysfunction (the control group) and six men who underwent ACLR of the left limb (group of patients). The control group was age, height and body mass matched. A data acquisition setup consisting of three independent modules including force platforms, position analysis system and electromyography was used. Subjects were jumping down from 0.1, 0.2, and 0.3 m step heights. The acquired signals were used to determine the ground reaction force, muscular activity, mass centre position, velocity and acceleration. Results: Statistically significant differences were found between the groups (t-test, $p < 0.05$) in the maximum vertical ground reaction force in the left limb for 0.2 and 0.3 m step heights. Differences in the muscle activity between the groups were found to be statistically significant (t-test, $p < 0.05$) before the jump, during the landing phase, and after the jump for selected muscle groups and step heights. Conclusion: Combing the three independent measurement systems provided new information on drop jump biomechanics. The distribution of loads in different muscles was not uniform across the groups. Patients allocated more energy to control their motion and seemed to protect their operated limb by shifting the bodyweight to the healthy limb.

Key words: *vertical ground reaction forces, muscle power, muscle activity, velocity, acceleration, mass centre reposition*

1. Introduction

Identification of human locomotor capacity is an important topic of biomechanics [28], [2]. It can be particularly useful in physiotherapy and rehabilitation engineering, for example, in assessing rehabilitation progress in patients with lower limb dysfunctions [31]. Those are often caused by Anterior Cruciate Ligament (ACL) injury, which constitutes one of the common ailments in athletes and active population [27], [5]. In order to treat the deficits, like instability and biomechanical alterations after such injury Anterior Cruciate Ligament Reconstruction (ACLR) became the most common treatment followed by post-surgery rehabilitation. In order to identify ACL injuries with overt clinical symptoms, an orthopaedist reviews the patient history and performs physical examination, which involves clinical tests such as the measurement of anterior–posterior dislocation of the knee [12], Lachman test and the pivot shift test, MRI and arthroscopy [29], [19]. Additionally, the identification of the ACL injury could be assessed by utilizing kinetic, kinematic and bioelectric data [6], [4], [3]. For post ACLR subjects, the above-mentioned methods of motion analysis can be conducted in different ways of locomotion activity such as walk, run or jump [30], [24], [15], [9], [32], [20]. Following an important body of works [32]–[38] [21], [18], [11], [10] we focus on the characteristics of drop jump in young male patients after ACLR and an age, gender, body height and body mass matched control group of sub-

---

* Corresponding author: Aleksandra Melińska, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-377 Wrocław, Poland. Tel: +48 607 88 77 47, e-mail: aleksandra.melinska@pwr.edu.pl

Received: October 23rd, 2014
Accepted for publication: December 30th, 2014

jects. We aim to assess jump performance of male subjects who underwent Anterior Cruciate Ligament Reconstruction (ACLR) through using the combined data acquisition setup, in which three independent modules including force platforms, position analysis system and electromyography provide information of the biomechanical characteristics of the drop jump.

2. Materials and methods

The considered analysis of the drop jump characteristics is based on the assessment of kinematic, kinetic and electromyography data. The study uses BTS Smart Capture three-module system consisting of: two force Kistler platforms, position analysis system and surface electromyography (BTS S.p.A, Garbagnate Milanese MI, Italy). The study was carried out at the Movement Analysis Laboratory at the College of Physiotherapy in Wrocław, Poland. Before examination, each subject was informed about the aim of the study and was requested to consent to his participation. A total of 28 male subjects aged 20 to 26 were studied: 22 did not show and were not diagnosed with any knee joint dysfunction (the control group) and six men who underwent ACLR of the left limb (group of patients). The patients went through a three-month supervised rehabilitation course in the Center of Rehabilitation in College of Physiotherapy (Wrocław, Poland) and then carried out a rehabilitation program themselves. The program of rehabilitation after ACLR was carried out according to the protocol described in [7]. Patients agreed to participate in the study eighth month after the surgery. The control group was age, body height and body mass matched. Data characterizing the groups (mean ±SD): (a) Control group: age [years] 25.1 ± 4.3; height [m] 1.78 ± 0.19; weigh [kg] 78.5 ± 9.7, (b) Patients: age [years] 26.2 ± 2.3; height [m] 1.72 ± 0.91; weigh [kg] 74.3 ± 5.6. All subjects were treated according to the tenets of the Declaration of Helsinki. The test was preceded by a short warm up involving trot (three to four minutes) followed by five–seven jumps and after a 20 second interval four to five squats. After a short break, the subject performed trial jumps from different heights. The jumps were followed by a two minute rest period. The first stage of the test involved the measurement of ground reaction forces and muscle activity during free standing on the force platforms. Next, subjects were instructed to jump from the steps of 0.1, 0.2, and 0.3 m in height. The step height was not randomized to ensure comfort for the group of patients. Note that after the warm up the learning effect was no longer of essence. There was a 30-second break between the jumps. The baseline position for each subject was free standing on both limbs on the step. On the examiner's command, the subject jumped down. Each subject was instructed to land on his toes and metatarsus on two limbs (each limb on each platform). The test setup is shown in Fig.1.

Each test comprised a series of measurements recording time-space, electromyography, kinetic and kinematic parameters. The measured system was synchronized. The measurement of ground reaction forces was performed using the force platform, which was integrated with the track of subject's movement. The measurement of ground reaction forces is possi-

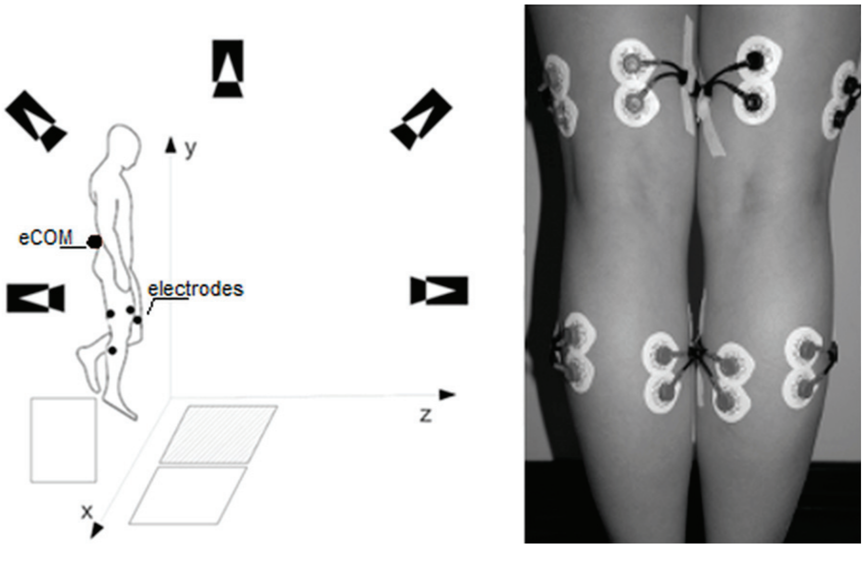

Fig. 1. Measurement system (left). Arrangement of electrodes and markers on the patient's body (right).
eCOM – estimated center of mass, electrodes (see Methods)

ble through piezoelectric phenomenon. Four electric converters are placed in the platform corners; when a patient stands on the platform, the transducers are deformed generating electric load. Then the load is stored and sent to the analogue-digital converter, from which the signal is sent to the processor. Strength is measured in three directions; however, the vertical component was selected for this analysis due to the nature of the movement being studied.

BTS Smart-D is the module performing the function of multichannel 3D navigation. For a single luminous marker, the system generates a 3D time array whose analysis is carried out in later stages of the experiment. During the tests, the subject had a marker placed on the sacral bone (Fig. 1). The marker estimates the position of body mass centre/gravity centre (eCOM). We decided to use only one marker in contrast to other studies, which focus on the role of lower and upper extremities in landing strategies [33], [1].

BTS Pocket EMG is the system of recording superficial EMG muscle activity. The measurement of muscular potential is possible through an adequate distribution of differential electrodes, which, while attached to the skin surface, collect muscular potential. EMG signals were recorded from four muscle groups for the right and left limbs (SR – semitendinosus right limb, GMR – gastrocnemius medialis right limb, GLR – gastrocnemius lateralis right limb, VMR – vastus medialis right limb, SL – semitendinosus left limb, GML – gastrocnemius medialis left limb, GLL – gastrocnemius lateralis left limb, VML – vastus medialis left limb). The EMG methodology was in accordance with SENIAM project guidelines [14]. Prior to electrode placement, the skin was disinfected to reduce resistance of the near electrode layer; the electrodes were placed so that the distance between them was not greater than 2 cm.

(a) Pre-processing of signals was carried out using BTS Smart Analyzer computer system, allowing experimental data management. Part of the experimental results was processed using a tailored program, specifically developed for the analysis including averaging filter. The signal from force platform contained noise which could be eliminated by a smoothing filter. We used Savitzky–Golay smoothing filter of degree two [26]. For the eCOM marker signal the average filter was used to facilitate numerical derivation of velocity and acceleration.

(b) Decimation. Signals from force platforms and motion capture system were not sampled with the same frequency (120 Hz motion capture and 960 Hz for platforms). A force signal necessitated subsampling [23].

2.1. Statistical analysis

The following tests were applied ($\alpha = 0.05$):

1. The Shapiro–Wilk test assesses whether the samples of the control group and patients come from normally distributed populations. We tested ground reaction force (F_{av}, $F_{\max}$, F_{free}) and all muscle activities during the landing phase, in free standing before and after the jump. The hypothesis of normality was retained for data from both subject groups.
2. The F-test assesses whether two normal populations have the same variance. We tested ground reaction force (F_{av}, $F_{\max}$) and all muscle activities (RMS/RMS$_{\mathrm{ref}}$) during the landing phase, in free standing before and after the jump.
3. The t-test assesses whether two sets of data have significantly different mean values. Similarly, as in the case of the F-test, we tested ground reaction force (F_{av}, $F_{\max}$) and all muscle activities (RMS/RMS$_{\mathrm{ref}}$) during the landing phase, in free standing before and after the jump.
4. Pearson product–moment correlation coefficient r is used to analyse interdependence, i.e., the strength of the correlation, between the ground reaction force and the muscle activity [25]. Determining the significance of coefficient r is conducted by using t-test.

3. Results

3.1. Ground reaction force

The landing phase of the drop jump movement is extracted from the force signal. It was assumed that it corresponds to time from the maximum of the force function to the moment when its values do not vary by more than 20% of the maximum value. Table 1 lists the measured group ground reaction forces (mean ±SD): the average force in landing phase $F_{av} = \Sigma_{i=1}^{n} \frac{F_i}{n}$, where F_i is a force value, n number of samples in period of time considered; the maximum force value ($F_{\max}$) and force value during free standing (F_{fr}). The ground reaction force is up to several times greater than in the case of free standing. For all step heights, the average reaction force (Table 1, F_{av}) in the left limb is less in patients than in control group, as is the case of free standing. In the right

Table 1. Ground reaction force

Step height [m]		F_{av} [N]		F_{max}[N]		F_{fr} [N]	
		Left limb	Right limb	Left limb	Right limb	Left limb	Right limb
0.1	CG	707 ± 117	678 ± 124	1505 ± 241	1464 ± 292	387 ± 58	373 ± 84
0.2		816 ± 140	764 ±153	1608 ± 286	1631 ± 303		
0.3		751 ± 101	801 ± 152	1681 ± 333	1702 ± 376		
0.1	P	346 ± 124	698 ± 121	1145 ± 322	1954 ± 143	372 ± 68	361 ± 84
0.2		576 ± 253	727 ± 110	1232 ± 330	1978 ± 112		
0.3		723 ± 264	760 ± 92	1380 ± 311	1983 ± 106		

F_{av} – average force in cushioning phase; F_{max} – maximum force value durnig jump; F_{fr} – average force value during free standing; CG – control group; P – patients.

Table 2. P-value for t-test for the ground reaction force and the muscle activity in control group and patients

Ground reaction force	SH [m]	F_{av} Right limb	F_{av} Left limb	F_{max} Right limb	F_{max} Left limb				
	0.1	0.14	0.22	0.48	0.21				
	0.2	0.48	0.14	0.43	**0.02**				
	0.3	0.26	0.34	0.25	**0.03**				
Muscle activity		SR	GMR	GLR	VMR	SL	GML	GLL	VML
Cushioning phase	0.1	0.52	0.36	0.63	0.64	0.51	0.35	**0.01**	0.82
	0.2	**0.01**	0.07	0.27	0.05	0.11	**0.01**	**0.04**	0.84
	0.3	**0.02**	0.22	0.2	0.14	0.21	0.07	0.22	0.07
Free standing before jump	0.1	**0.03**	0.64	0.24	0.11	0.4	0.29	0.2	**0.001**
	0.2	0.2	0.91	0.09	0.36	0.2	0.38	**0.02**	**0.001**
	0.3	**0.001**	0.3	0.98	0.05	**0.02**	0.32	0.06	**0.001**
Free standing after jump	0.1	0.07	0.73	0.18	0.26	0.84	0.54	0.63	0.65
	0.2	0.28	0.88	**0.04**	0.28	0.92	0.74	0.08	0.77
	0.3	0.12	0.85	**0.04**	0.09	**0.001**	0.06	**0.01**	0.86

Note: SR – semitendanosus right limb, GMR – gastrocnemius medialis right limb, GLR – gastrocnemius lateralis right limb, VMR – vastus medialis right limb, SL – semitendanosus left limb, GML – gastrocnemius medialis left limb, GLL – gastrocnemius lateralis left limb, VML – vastus medialis left limb, F_{av} – average force in cushioning phase, F_{max} – maximum force value durnig jump, CG – control group, P – patients, SH – step height.

limb case, F_{av} is lesser for the patients than in control group, except for the 0.1 m step, where it is slightly greater in patients. F_{max} in the left limb is greater in control group, but in the case of right limb is greater for patients. For the control group it is approximately four times greater than free standing value while in the case of patients, it is approximately up to five times greater.

It should be noted that the results of patients are characterized by a larger data variation than the control group. Significant differences between the groups were found in F_{max} for drop jump from the height of heights of 0.2 and 0.3 in left limb (t-test, $p < 0.05$, Table 2).

3.2. Body mass centre position

The temporal variation in the position of eCOM marker is used to determine the velocity and acceleration. Figure 2 shows examples of the momentary (temporal) velocity (2a) and acceleration (2b) for a healthy individual and a patient jumping of a 0.1 m step.

The momentary velocity v_n and acceleration a_n for two adjacent samples of eCOM position are given by

$$v_n = v(t_n) = \lim_{\Delta t \to 0} \frac{\Delta s}{\Delta t} = \frac{s(t_{n+1}) - s(t_n)}{t_{n+1} - t_n}, \qquad (1)$$

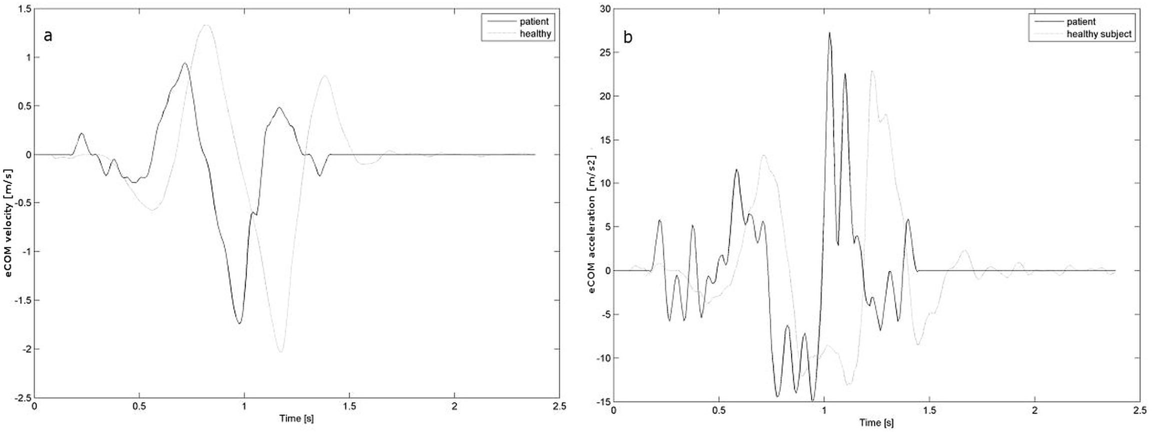

Fig. 2. (a) Average momentary velocity for one patient and one subject from control group,
(b) Average momentary acceleration for one patient and one subject from control group

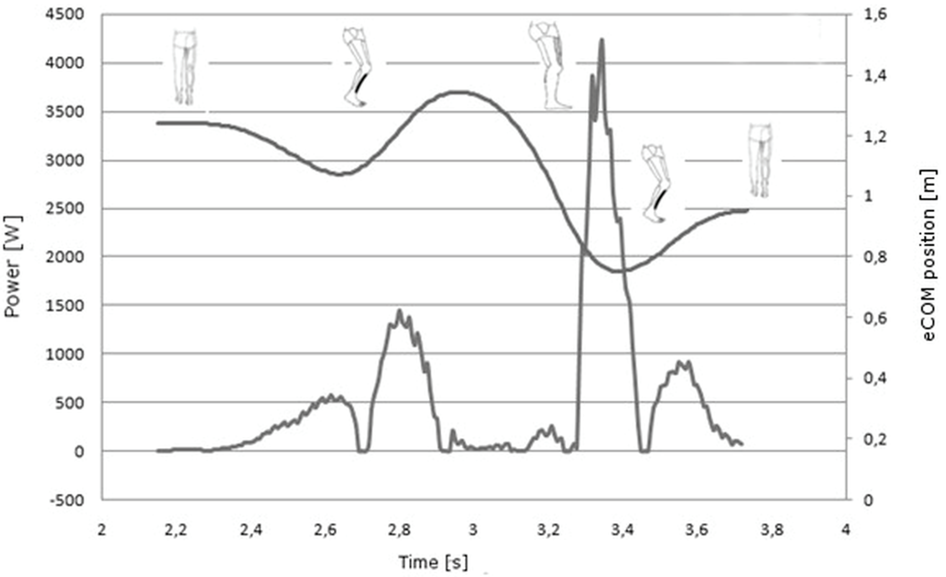

Fig. 3. Power generated by the system during drop jump for one subject from control group

$$a_n = a(t_n) = \lim_{\Delta t \to 0} \frac{\Delta v}{\Delta t} = \frac{v(t_{n+1}) - v(t_n)}{t_{n+1} - t_n}, \qquad (2)$$

where $s(t_n)$ is the marker position in time t_n.

Differences between the healthy subject and the patient are evident for both parameters. The patient's results are characterized by lesser values of momentary velocity but a greater spread in momentary acceleration. That means that a patient allocates much more energy to control his motion.

The power of the human locomotor system can be related to velocity and acceleration,

$$P = \lim_{\Delta t \to 0} \frac{\Delta W}{\Delta t} = \lim_{\Delta t \to 0} \frac{F \Delta s}{\Delta t}$$

$$= \lim_{\Delta t \to 0} m \Delta a v = m v_n (a_{n+1} - a_n) \qquad (3)$$

where W – work, t – time, F – force, s – reposition, m – mass of subject, a – acceleration, and v – velocity.

Figure 3 shows the power generated by the system during drop jump in relation to eCOM position for one healthy subject.

The graph shows the moment of drop jump at which the muscles are most involved. Specifically, in the phase of lowering the mass centre, corresponding to flexing of the knees before the jump, the power increases to the value of approximately 500 W. This corresponds to about 1/3 of the value of the power generated during muscle involvement when the body is clearing the surface of the step. Next, power fluctuates slightly above zero, with the simultaneous lowering of eCOM. This means that during the fall the muscles remain at rest, after which the power rapidly increases and reaches the maximum of about 4200 W during the landing of the subject on the platform. The level of increased involvement of the muscles persists until the balance is regained after the drop jump, which can be observed in the form of fluctuations of power values. This enables calculation of the work done by the muscles. For this particular example, it amounts to approximately 2100 J.

3.3. Electromyography

The muscle activity is measured during the landing phase (Fig. 4a), as well as before (Fig. 4b) and after (Fig. 4c) drop jump from each step height (mean ± SD). EMG signals have been normalized by dividing the

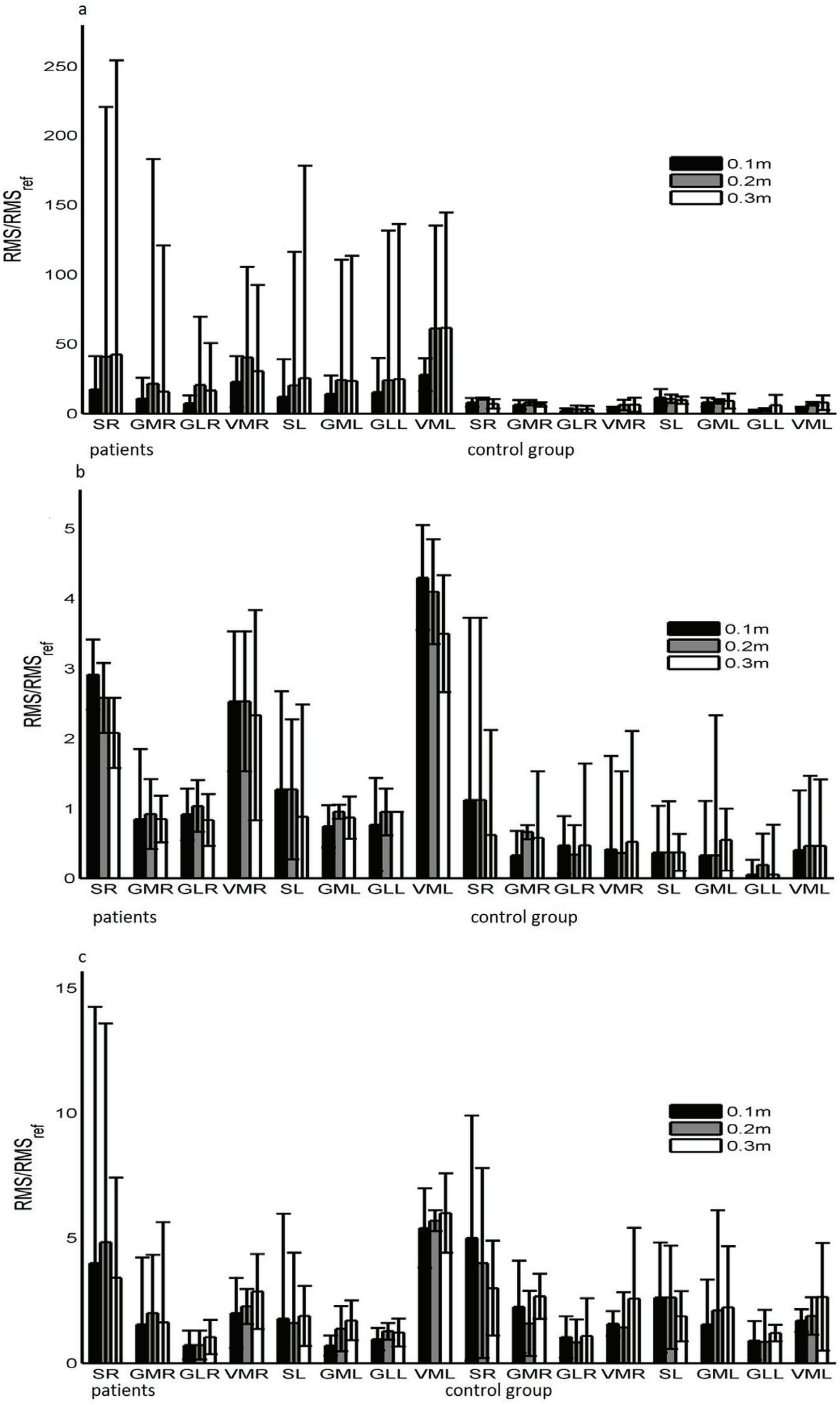

Fig. 4. (a) Comparison of RMS values in the cushioning phase in control group and patients.
(b) Comparison of RMS values while standing free before drop jump.
(c) Comparison of RMS values while standing free after drop jump

value of EMG signals by a reference EMG (RMS_{ref}) value obtained from the same muscle in free standing. Figure 4 shows RMS/RMS_{ref} ratios for each measured group.

3.3.1. Landing phase

Patients are characterized by the greatest activity in all muscles in both limbs than the control group. The greatest muscle activity is observed in the vastus medialis muscle (VML, VMR), both in the right and left limb. Also, substantial activity is demonstrated by the semitendinosus muscle (SL, SR). Both muscles are characterized by a higher activity in the right than in the left limb (Fig. 4a).

Table 3. Pearson product–moment correlation coefficient *R* between the ground reaction force and muscle activity

		SH [m]	SR	GMR	GLR	VMR	SL	GML	GLL	VML
CG	*r*	0.1	0.28	0.11	0.21	0.17	0.16	–0.41	–0.32	–0.06
	p		0.47	0.78	0.59	0.66	0.67	0.28	0.41	0.89
	r	0.2	0.67	0.66	0.70	0.12	–0.40	–0.38	–0.37	–0.36
	p		0.05	0.05	0.03	0.76	0.29	0.31	0.33	0.34
	r	0.3	–0.29	0.92	–0.84	0.78	1.00	–0.98	0.98	0.06
	p		0.45	0.001	0.001	0.01	0.00	0.001	0.001	0.88
P	*r*	0.1	–0.10	0.98	0.93	0.93	0.69	–0.51	–0.54	0.95
	p		0.80	0.001	0.001	0.001	0.04	0.17	0.13	0.001
	r	0.2	0.66	0.76	0.64	0.21	0.99	–0.72	–0.70	–0.18
	p		0.05	0.02	0.06	0.59	0.001	0.03	0.04	0.64
	r	0.3	–0.29	0.92	–0.84	0.78	1.00	–1.00	0.98	0.06
	p		0.45	0.001	0.001	0.01	0.001	0.001	0.001	0.88

Note: *r* – Pearson's coefficient. *p* – value of determining the significance of coefficient *r*; SR – semitendanosus right limb, GMR – gastrocnemius medialis right limb, GLR – gastrocnemius lateralis right limb, VMR – vastus medialis right limb, SL – semitendanosus left limb, GML – gastrocnemius medialis left limb, GLL – gastrocnemius lateralis left limb, VML – vastus medialis left limb, CG – control group, P – patients, SH – step height.

3.3.2. Before the drop jump

In both groups, activity is greater in all muscles before drop jump than after jump. It is also important that the values of activity before drop jump are substantially (approximately 3–4 times) greater in patients than in control group. The greatest muscle activity occurs in the vastus medialis muscle in both groups (VML, VMR).

In the case of control group the height of the step on which the person preparing for the jump stands does not alter the results whereas in the case of patients with dysfunctions there are visible differences in the average values. Also patients show greater muscle activity when preparing for drop jump from 0.2 m step (Fig. 4b).

3.3.3. After the drop jump

The muscle activity values are spread. In almost every case, the muscle activity is greater at drop jump from the 0.2 m step, rather than from the 0.3 m step. After the jump, the muscle activity is greater for patients than for control group for vastus medialis and semitendinosus muscles (VMR, VML, SR) (Fig. 4c).

We observe substantial differences in the means of groups, but large standard deviations are also evident. Hence tests for determining the statistically significant differences are necessary (Table 3).

4. Discussion

We focus on male subjects, because the overall project goal aims at evaluating a pilot comprehensive rehabilitation program for men. Gender differences were extensively covered in other works [21], [18], [8], For example, McNeal et al. [18] aimed at investigating the effects of a maximum repeated-jumps task on force production, muscle activation and kinematics in relation to gender. They conclude that subjects reduce muscle activation and force production and alter jumping technique. However, the changes are not dependent on gender. Fagenbaum and Darling [10] present jump landing strategies in male and female college athletes and the implications of such strategies for ACL. They demonstrate that women land with greater knee flexion angles and greater knee flexion accelerations than men. They also show that the knee muscle activation patterns are generally similar in men and women.

In our test setup we considered drop jump from the steps of three different heights (0.1, 0.2, 0.3 m). There are other studies related to jump, but they consider different step heights or assumptions. McElveen et al. [17] present the analysis of the vertical drop jump too. They study the values of ground reaction forces for the vertical component of jump, its height and peak power. They also evaluate reciprocal correlations between these parameters and asymmetry levels, comparing the results obtained from the dominant lower limbs with those obtained from non-dominant limbs in young male and female subjects. They emphasize the significance of objective biomechanical studies in fitness assessment and the significance of the assessment of symmetry of the biomechanical parameters obtained from the lower limbs during jumps. The muscle activation and ground reaction force are not the only assessing methods of the drop jump. For example, Graham-Smith and Lees [11] aim to conduct a three-dimensional analysis of the touch-down to take-off phase in the long jump. They use the vertical velocity in a series of correlational and multiple regression analyses.

A self-contained area of interest in drop jump task is the landing phase. Several studies consider this particular phase [16], [13], [8]. In the light of currently available knowledge, the analysis presented provides new information on the aspects related to the system energy and the way of drop jump landing for patients with knee injuries and the control group. The most important findings are summarized as follows.

Despite having small sample size, significant differences are present in the case of the maximum ground reaction force in reconstructed limb for 0.2 and 0.3 m step heights (*t*-test, $p < 0.05$). Taking into account the value of the reaction force measured at free standing, the patients exhibited greater average force value in the non-operated limb than that recorded in the control group. It turns out that patients who underwent ligament reconstruction protect their operated limb by shifting the bodyweight to the healthy limb.

In the landing phase, the muscle activity is greater in patients than in the control group. Significant differences (*t*-test, $p < 0.05$) are found in the muscles: SR for 0.2 and 0.3 m, GML for 0.2 m, GLL for 0.1 and 0.2 m step height.

Muscle activity is greater before drop jump in both control group and patients with limb dysfunctions. In both groups being tested, muscle activity increased prior to drop jump. Also, the muscle activity in patients did not increase with the step height. We suggest that a patient takes more caution of a drop jump during the first jump at a height of 0.2 m, but after finding out it is safe, such an individual is no longer concerned to drop jump from a height of 0.3 m. Significant differences are found in the muscles: SR for 0.1, 0.3 m step height, GMR for 0.1, 0.3 m., SL for 0.3 m., GLL for 0.2 m, VML for 0.1, 0.2, 0.3 m step height (*t*-test, $p < 0.05$). After the jump, significant differences are found in GLR for 0.2 and 0.3 m step height and for GLL and SL for 0.3 m.

Generally, the correlation between the ground reaction force and muscle activity is statistically significant (*F*-test, $p < 0.05$) in patients for every step height and for most of the muscles, whereas in the control group, the correlation is asserted only for 0.2 and 0.3 m step heights.

It should be noted that the group of patients underwent an average of 3 months post-operative outpatient physiotherapy. Biomechanical study and electrophysiological study during drop jump with varying heights were conducted eight months after ACLR. This means that at the time of the study, the patients did not have the full third stage of physiotherapy, which lasts up to 5 months after the ACLR, and then the last, fourth stage of physiotherapy which is conducted individually for 6 months, or even up to 8 months after the ACLR [15]. In the third stage and especially in the last fourth stage postoperative physical therapy restores the patients strength, power and jumping. During the last two stages of physiotherapy, resistance training for large muscle groups, including the muscles acting on the operated knee, is performed. Other exercises performed include eccentric and concentric exercises with gradual resistance, dynamic exercise improving proprioception and neuromuscular coordination for the lower extremities and the entire body. Various forms of running with changing directions are restored. Jumps and hops, as well as one leg jumps and plyometric training are performed. This is a functional training of the whole body, as well as athletic preparation of the patient. Probably the lack of implementation of the third stage and the last of the fourth stages of physiotherapy in patients was responsible for the asymmetries observed in the measured reaction forces. Therefore, in patients an increased muscle tone bands on the side of the operated limb have been reported in electromyography in relation to the control group. This could indicate an increased jump-down control in the absence of full neuromuscular coordination. This was particularly visible before landing, as well as during the landing and the ground–feet contact with parallel suppression of the drop jump – despite eight months after ACLR. Paterno et al. [22] presented clinical implications of this phenomenon. In their studies they pointed out that asymmetry in jump-downs and related disorders of the neuromuscular coordination can increase the risk of muscle injury of knee joints, and may also increase the risk of further injuries of ligaments' reconstruction after ACL.

5. Conclusions

Summarizing the results, combing the three independent measurement systems provide new information on biomechanical locomotive system during the drop jump for both groups of control group and people with knee injuries or other limb dysfunctions.

The study uses in vivo biomechanics methods and may serve as reference for the evaluation of the level of restored jumping capability in patients with lower limb injuries during the last stages of physiotherapy – rehabilitation. The test may also be applied to assess the usefulness of specific exercises in physiotherapy programs aimed at improving the dynamics and symmetry of jumping as well as the enhancement of neuromuscular coordination and proprioception in its wide context.

References

[1] ASHBY M.B., HEEGAARD J.H., *Role of arm motion in the standing long jump*, J. Biomech., 2002, 35(12), 1631–1637.

[2] BACHSCHMIDT R.A., HARRIS G.F., SIMONEAU G.G., *Walker-assisted gait in rehabilitation: a study of biomechanics and instrumentation*, IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2001, 9(1), 96–105.

[3] BEARD D.J., SOUNDARAPANDIAN R.S., O'CONNOR J.J., DODD C.A., *Gait and electromyographic analysis of anterior cruciate ligament deficient subjects*, Gait & Posture, 1996, 4(2), 83–88.

[4] BISSELING R.W., HOF A.L., BREDEWEG S.W., ZWERVER J., MULDER T., *Relationship between landing strategy and patellar tendinopathy in volleyball*, Br. J. Sports Med., 2007, 41(7), e8–e8.

[5] BJORDAL J.M., ARNOY F., HANNESTAD B., STRAND T., *Epidemiology of anterior cruciate ligament injuries in soccer*, Am. J. Sports Med., 1997, 25(3), 341–345.

[6] CAPPELLO A., STAGNI R., FANTOZZI S., LEARDINI A., *Soft tissue artifact compensation in knee kinematics by double anatomical landmark calibration: performance of a novel method during selected motor tasks*, IEEE Transactions on Biomedical Engineering, 2005, 52(6), 992–998.

[7] CZAMARA A., TOMASZEWSKI W., BOBER T., LUBARSKI B., *The effect of physiotherapy on knee joint extensor and flexor muscle strength after anterior cruciate ligament reconstruction*, Med. Sci. Monit., 2011, 17(1), 35–41.

[8] DECKER M.J., TORRY M.J., WYLAND D.J., STERETT W.I., STEADMAN J.R., *Gender differences in lower extremity kinematics, kinetics and energy absorption during landing*, Clin. Biomech., 2003, 18(7), 662–669.

[9] DEVITA P., HORTOBAGYI T., BARRIER J., TORRY M., GLOVER K.L., SPERONI D.L., MONEY J., MAHAR M.T., *Gait adaptations before and after anterior cruciate ligament reconstruction surgery*, Med. Sci. Sports Exerc., 1997, 29(7), 853.

[10] FAGENBAUM R., DARLING W.G., *Jump landing strategies in male and female college athletes and the implications of such strategies for anterior cruciate ligament injury*, Am. J. Sports Med., 2003, 31(2), 233–240.

[11] GRAHAM-SMITH P., LEES A., *A three-dimensional kinematic analysis of the long jump take-off*, J. Sports Sci., 2005, 23(9), 891–903.

[12] HESSE D., CHAHAL J., WHITE L.M., WHELAN D.B., *Nonoperative management of an extra-articular dislocation of the posterior horn of the lateral meniscus with clinical and mri correlation: a case report*, Clin. J. Sport Med.: official journal of the Canadian Academy of Sport Medicine, 2009, 19(4), 333–335, LR: 20131121; JID: 9103300; ppublish.

[13] HEWETT T.E., MYER G.D., FORD K.R., SLAUTERBECK J.R., *Preparticipation physical examination using a box drop vertical jump test in young athletes: the effects of puberty and sex*, Clin. J. Sport Med., 2006, 16(4), 298–304.

[14] HERMENS H.J., FRERIKS B., MERLETTI R., STEGEMAN D., BLOK J., RAU G., DISSELHORST-KLUG C., HAGG G., *European recommendations for surface electromyography*, http://www.seniam.org/

[15] KNOLL Z., KISS R.M., KOCSIS L., *Gait adaptation in acl deficient patients before and after anterior cruciate ligament reconstruction surgery*, J. Electromyogr. Kinesiol.: Official journal of the International Society of Electrophysiological Kinesiology, 2004, 14(3), 287.

[16] LEONTIJEVIC B., PAZIN N., BOZIC P.R., KUKOLJ M., UGARKOVIC D., JARIC S., *Effects of loading on maximum vertical jumps: Selective effects of weight and inertia*, J. Electromyogr. Kinesiol., 2012, 22(2), 286–293.

[17] MCELVEEN M.T., RIEMANN B.L., DAVIES G.J., *Bilateral comparison of propulsion mechanics during single-leg vertical jumping*, J. Strength Cond. Res., 2010, 24(2), 375–381.

[18] MCNEAL J.R., SANDS W.A., STONE M.H., *Effects of fatigue on kinetic and kinematic variables during a 60-second repeated jumps test*, Int. J. Sport Psychol., 2010, 5(2), 218–229, JID: 101276430; ppublish.

[19] MILANKOV M., RAŠOVIĆ P., KOVAČEV N., MILOVIĆ M., BOJAT V., *Fracture of the patella after the anterior cruciate ligament reconstruction*, Medicinski pregled, 2012, 65(11–12), 476–482.

[20] MRDAKOVIC V., ILIC D., VULOVIC R., MATIC M., JANKOVIC N., FILIPOVIC N., *Leg stiffness adjustment during hopping at different intensities and frequencies*, Acta Bioeng. Biomech., 2014, 16(3), 70–76.

[21] PAPPAS E., HAGINS M., SHEIKHZADEH A., NORDIN M., ROSE D., *Biomechanical differences between unilateral and bilateral landings from a jump: gender differences*, Clinical Journal of Sport Medicine: Official journal of the Canadian Academy of Sport Medicine, 2007, 17(4), 263–268, LR: 20131121; JID: 9103300; ppublish.

[22] PATERNO M.V., SCHMITT L.C., FORD K.R., RAUH M.J., MYER G.D., HUANG B., HEWETT T.E., *Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport*, Am. J. Sports Med., 2010, 38(10), 1968–1978.

[23] PHARR M., HUMPHREYS G., *Physically based rendering: From theory to implementation*, Morgan Kaufmann, 2010.

[24] PIETRASZEWSKI B. RUTKOWSKA-KUCHARSKA A., *Relative power of the lower limbs in drop jump*, Acta Bioeng. Biomech., 2011, 13(1), 13–18.

[25] RAHMAN N.A., MACPHERSON A.S., ROSEMBLATT K.A. APPELBAUM N.P., *A Course in Theoretical Statistics: For Sixth Forms*, Technical Colleges, Colleges of Education, Universities. Griffin London, 1968.

[26] SAVITZKY A., GOLAY M.J., *Smoothing and differentiation of data by simplified least squares procedures*, Anal. Chem., 1964, 36(8), 1627–1639.

[27] SHEA K.G., GRIMM N.L., EWING C.K., AOKI S.K., *Youth sports anterior cruciate ligament and knee injury epidemiology: who is getting injured? in what sports? when?*, Clin. Sports Med., 2011, 30(4), 691–706, JID: 8112473; ppublish.

[28] SIEGEL L., VANDENAKKER-ALBANESE C., SIEGEL D., *Anterior cruciate ligament injuries: anatomy, physiology, biomechanics, and management*, Clin. J. Sport Med.: official journal of the Canadian Academy of Sport Medicine, 22(4), 349–355, JID: 9103300; ppublish.

[29] STREICH N.A., REICHENBACHER S., BARIE A., BUCHNER M., SCHMITT H., *Long-term outcome of anterior cruciate ligament reconstruction with an autologous four-strand semitendinosus tendon autograft*, Int. Orthop., 2013, 37(2), 279–284.

[30] TERRIER P., LUTHI F., DERIAZ O., *Do orthopaedic shoes improve local dynamic stability of gait? an observational study in patients with chronic foot and ankle injuries*, BMC Musculoskelet. Disord., 2013, 14, 94.

[31] TRAJKOVSKI A., OMEROVIC S., KRASNA S., PREBIL I., *Loading rate effect on mechanical properties of cervical spine ligaments*, Acta Bioeng. Biomech., 2014, 16(3), 13–20.

[32] WINIARSKI S., RUTKOWSKA-KUCHARSKA A., *Estimated ground reaction force in normal and pathological gait*, Acta Bioeng. Biomech., 2009, 11(1), 53–60.

[33] WITHROW T.J., HUSTON L.J., WOJTYS E.M., ASHTON-MILLER J.A., *The effect of an impulsive knee valgus moment on in vitro relative acl strain during a simulated jump landing*, Clin. Biomech., 2006, 21(9), 977–983.