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# EFFECT OF SYSTEMATIC LANDING TRAINING ON KNEE KINEMATICS AND GROUND REACTION FORCES IN YOUNG ADULTS

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**Abstract:**
In gymnastics, the final landing position represents a key determinant of safety and exercise quality. Previous findings on the biomechanics of landing indicated that knee flexion correlates strongly with ground reaction forces. However, it remains unclear how this relationship is affected by landing training. We conducted a randomized controlled study to assess the effect of systematic landing training on knee kinematics and ground reaction forces in young adult beginner gymnasts. The study included three-dimensional motion analysis of knee flexion and measurement of ground reaction forces for landings from heights of 37 and 87cm. Of the 28 beginner gymnasts who participated in the study, 14 underwent five weeks of landing training, whereas 14 served as controls (no intervention). A significant pre-post difference (-11.2°) was observed only for the control group, and only regarding maximum knee flexion after landings from heights of 37cm. Although no significant effects were noted overall for the training group, systematic landing training seems effective for correcting those landings that deviated strongly from the target position prior to training initiation (37cm, r=-0.74; 8cm, r=-0.77; both with p< 0.01). Thus, while landing training appears to minimize peak forces at ground contact, our findings cannot be explained solely in terms of knee kinematics, warranting muscle activity analysis.

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**Keywords:** kinematics, ground reaction force, gymnastics athletes, landing training

## 1. Introduction

During freestyle competitions, the competitive gymnastics athlete performs a minimum of eight self-selected, gymnastic elements on the floor or on a parkour. These elements usually include jumps and rotations around corresponding body axes, all followed by landings. The desired landing posture in gymnastic competitions is mandated by the Code of Points (2017-2020), issued by the Fédération Internationale de Gymnastique (FIG) (2013) to ensure a safe landing technique to prevent athletes from injuries. Penalized deviations include sidesteps and excessive flexion of the lower limb (e.g., a deep squat upon landing is to be penalized by 0.5 points). An appropriate landing technique is required to ensure the implementation of these requirements.

In general, landing techniques can be clustered in two principal strategies either toe-heel (forefoot) or heel-toe (rear-foot), which strongly depend on the sport, the athletes' preference, and their physiological requirements (Cortes et al., 2007). The rear-foot strategy is commonly used during moderate speed running (Dufek & Bates, 1990), and the forefoot strategy is used in actual jump landings (Schot & Dufek, 1993) such as basketball and volleyball (Bressel & Cronin, 2005) showing lower maximal vertical ground reaction forces (vGRF) compared to the rear-foot strategy (Cronin, Bressel & Finn, 2008).

Landings in gymnastics also follow the forefoot strategy, and here, De Vita and Skelly (1992) categorized landings into stiff and soft, based on the maximum knee flexion noted after ground contact (Čuk & Marinšek, 2013; Marinšek, 2010). The assignment of the landings into these categories depends on the change in knee angle from the initial ground contact until the final position (stiff<90°, avg.=77°; soft>90°, avg.=117°) and the duration of the ground contact phase (stiff<152ms; soft>342ms). Within the framework of forefoot strategy, stiff and soft landings differ substantially with regards to vertical ground reaction force (vGRF) as the joint range of motion allows the knee muscles to absorb external load (Cortes et al., 2007).

The vGRF is a sensitive predictor of the external load on the musculoskeletal system (Paddle and Maulder, 2013) and was reported with magnitudes of 2–4 times the body weight (BW) while landing from vertical jumps (McNitt-Gray, 1993). Landing after complex exercises, such as double somersault, causes even higher vGRFs with up to 18 times BW (McNitt-Gray, 1993). Christoforidou et al. (2017) enrolled young, trained women and reported vGRFs of about 4 and 4.5 times BW upon vertical landing from drop jumps of 40 and 60cm heights, respectively. Although the height of the landing seems to be the determining factor of the external load, the type of floor, and the type of footwear, the landing technique also plays a key role (McNitt-Gray, Yokoi & Millward, 1994).

During successful landings, the gymnast is capable to control these high external load by actively coordinating the knee kinematics, which allows an optimal muscular force absorption with (Christoforidou et al., 2017; Marinšek & Čuk, 2010; Verniba, Vescovi, Hood & Gage, 2017). The modeling study of De Vita and Skelly (1992) showed that, compared to stiff landings, soft landings could absorb up to 19% more kinetic energy, suggesting that soft landings may be safer.

If the landing knee angle is too small (rather stiff landing) at initial contact, there is a high risk of injury to the lower extremities (Marinšek & Čuk, 2010). Various studies (Hume & Steele, 2000) have confirmed that most of the landing-related injuries are due to sudden decelerations or the knee is almost extended during the landing maneuver. These aspects are consequently making the knee the most frequently injured joint in floor gymnastics and court sports, which sports have similar deceleration patterns in common (Paddle & Maulder, 2013). Thus, adequate training must include both a variable and quick availability of appropriate responses to unexpected landing situations and, likewise, an automation of the correct final landing position.

Although there are no evaluated training programs in gymnastics, it is recognized that such systematic landing training improves safety upon landing. Araujo, Cohen, and Hayes (2015) enrolled 16 capoeira athletes and reported that a 6-week landing training program including elements of dynamic core stability training led to a significant reduction in GRF which is also associated with a lower probability of anterior cruciate ligament injury (Hewett et al., 2005). The authors focused their training program on strengthening the muscles of the lower extremities and the training of a variable availability of motor responses to changing landing situations. Especially, the training of motor skills corresponds to the results of studies that found correlations between motor control, external load (McNair & Prapavessis, 1999; Paddle & Maulder, 2013) and the injury risk (Mills, Pain & Yeadon, 2008) of gymnasts. However, whether a systematic training program of similar length affects landing strategies or parameters in gymnasts has not been investigated so far.

Since differences in landing heights put different demands on the landing strategies, the purpose of this study was to compare the ground reaction forces and knee angles involved in drop jump landings from two different heights. It was hypothesized that a 5-week systematic training of the availability of appropriate responses to unexpected landing situations and finishing in the final landing position defined by the FIG (2013) would result in lower vertical ground reaction forces and lesser knee flexion for both drop jump heights.

## 2. Methods

### 2.1. Participants

This study enrolled young adult gymnasts who volunteered to participate and provided written informed consent. All procedures were conducted following the principles set out by the Declaration of Helsinki, by relevant legislation, and by the local ethics committee, which had approved the study design.

Based on the results of Araujo, Cohen, and Hayes (2015) (Peak vGRF) an a priori power analysis was conducted using G*Power3 (Faul, Erdfeller, Lang & Buchner, 2007) to test the difference between two independent group means using a two-tailed test (Wilcoxon-Mann-Whitney test), a medium effect size (d=0.85), and an alpha of 0.05. Result showed that a total sample of 28 participants with two equal-sized groups of n=14 was required to achieve a power of 0.81. Consequently, twenty-eight gymnasts were enrolled and randomly assigned to the test group (TG) or the control group (CG). TG gymnasts participated in training sessions specifically focused on improving the landing technique (i.e., landing training), whereas CG gymnasts did not receive any landing-focused training in addition to their regular training. The training of the CG focused during the study period on floor exercises with a maximum of two 60 minutes-training sessions per week. Landings from heights were no central subject of the training. Athletic training was focused on increasing mobility at this time to provide a better contrast to TG training. Athletes with acute injuries of the back or lower limbs were excluded from this study. In the CG (n=14), the age was 21±1.8years, body weight was 70.14±9.84kg, and height was 177.64±7.97cm. In the TG (n=14), the age was 22.86±3.68years, body weight was 70.86±11.27kg, and height was 175.79±11.16cm. All participants were classified as adult beginners, with less than one year of gymnastics experience. The self-reported athletic biography included swimming, soccer, handball and, unsystematic fitness training.

**2.2. Systematic landing training protocol**

The training protocol used in this study was developed based on the protocol described by Araujo, Cohen, and Hayes (2015). The strength of the training concept lies in the shortness of the program, which allows it to be included in a priority program to sensitize the athletes for the correct movement execution. The variation of the landing stimuli targets a flexible availability of motor solutions for different landing tasks. Due to the limited availability of the participants, the duration of the training intervention was reduced from 6 to 5 weeks. Landing training was conducted twice a week, with an interval of 2 days between the sessions, and focused mainly on conditional aspects and the development of motor control. Specifically, the 5-week training intervention was structured as a Tabata workout (Tabata et al., 1996) on weeks 1 and 3, as circuit training on weeks 2 and 4, and as landing parkour on week 5.

Tabata training employed the traditional 20–10 routine (i.e., 20 seconds of maximal efforts followed by 10seconds of rest). The circuit training included relatively low loads for a relatively high number of repetitions in each set to improve local muscular and aerobic endurance (Fry, 2005). All sessions included aspects of coordination, strengthening, stabilization, and activation. The landing parkour involved numerous jump exercises from different heights and with strategies (e.g., straight jump, squat jump, straddle vault, one-leg jump, two-leg jump, ½ rotation, full rotation), landing in the final posture defined by the FIG (2013).

Each training session lasted approximately 30minutes and was structured into three parts (warming-up, stretching, and landing training), all supervised by experienced trainers. The 10minutes warm-up contained general and specific warm-up exercises (e.g., including high knees, buttock kicks, lunges, squats, and jumps), followed by dynamic stretching focusing on the demands associated with the subsequent training (e.g., stretching of hip extensors and knee flexors). The main part included motor training of the landing position, followed by plyometric, eccentric, and proprioceptive training. All training set-ups included only exercises with the participant's own BW, drop jumps from different heights, jumps over obstacles, and landing into the defined landing posture on different surfaces. Each week was assigned a special training (A-D), which is carried out two times a week (see Table 1). A detailed description of the training as video tutorials can be found on https://kielmotionlab.com/landungstraining/ or in the appendix. The target landing posture was defined at knee flexion <90°, torso flexion of 30–40°, and the arms raised anteriorly by about 120°. One week before and after the systematic landing training, both the training and the control group performed a landing analysis to evaluate the effect of the training on the landing mechanisms.

**2.3. Data collection**

The test for the pre- and post-systematic landing training data collection included three drop landings from a plateau onto a force plate (10N threshold, A9260, 1000Hz; Kistler, Winterthur, Switzerland) with a marked landing area of 30×30cm (De Vita & Skelly, 1992; McNitt-Gray, 1993; Mills et al., 2008; Verniba et al., 2017). The force plate was placed at 10 cm in front of the plateau, which was set at heights of 37 and 87cm. Unilateral motion analysis was conducted, per the protocol described by De Vita and Skelly (1992) and inertial measurement unit sensors (100 Hz; Noraxon USA Inc., Scottsdale, AZ, USA) were placed on the right pelvis, thigh, lower leg, and dorsal foot to investigate the knee flexion-extension angle (Struzik, Juras, Pietraszewski & Rokita, 2016). The system's measurement error for joint angle estimations during dynamic motions is reported to be less than 0.5° (Noraxon USA Inc., Scottsdale, AZ, USA). The force plate and inertial measurement unit data were synchronized within the MyoMotion software package, and no additional data processing in terms of filtering was applied.

Neoprene bandages were used to secure the sensors on each body segment. The participants wore their own footwear, which was the same during the pre-post measurements. The sensor set-up was calibrated before the final repetition to identify the sensor-to-segment orientation and to reduce the bias associated with sensor drifting (Seel, Raisch & Schauer, 2014). For this purpose, the participants were asked to stand in a t-pose, standing upright with legs straight and arms stretched parallel to the ground.

**Table 1:** Systematical program of 5 weeks landing training evaluated in this study

| Week | Warm Up | Video Reference | Training format | Stations | TG Exercise | TG Exercise's purpose | Concurrent training of TG and CG |
|---|---|---|---|---|---|---|---|
| Time | 10' | | 10 - 15' | | | | Twice a week |
| I | **Standard Warm Up** incl.<br><br>**General Warm Up** (e.g. easy running)<br><br>**Specific Warm Up** (e.g. skipping, running knee raises, heel kicks, ankle jumps back and forward, jumping knee raises, walk on toes, deep squat walking)<br><br>**Dynamical Stretching** | A | **Tabata**<br>- 20" high intensity<br>- rest for 10"<br>- complete 8 stations<br>- rest for 2'<br>- repeat once | 1 | left single leg lunges | Strengthening and conditioning of lower leg muscles | Duration: max. 60' (incl. Warm-up)<br>Focus: Balance and upper body strength<br>Exercises (e.g.):<br>- Balance parcour<br>- Throwing and catching on the balance beam<br>- Freezing in e.g. single leg standing positions on varying grounds<br>- Upper body circle training (min. 20') |
| | | | | 2 | right single leg lunges | | |
| | | | | 3 | jumping single leg lunges | | |
| | | | | 4 | lunges against resistant band | | |
| | | | | 5 | drop jumps from different heights | | |
| | | | | 6 | Jumping on a soft ground | | |
| | | | | 7 | ankle dips | | |
| | | | | 8 | running knee raises on a soft ground | | |
| II | | B | **Circuit**<br>- 20' reps moderate intensity<br>- rest for 10"<br>- complete 8 stations<br>- rest for 2'<br>- repeat once | 1 | stand forefeet and catch | Postural control and stability. Flexible availability of motor adaptation to different surfaces. | Duration: max. 60' (incl. Warm-up)<br>Focus: Balance and upper body flexibilty<br>Exercises (e.g.):<br>- Standing on challenging surfaces (e.g. balls)<br>- Walking on small surfaces<br>- Intensive stretching (min. 20') |
| | | | | 2 | singe leg hurdle jumps | | |
| | | | | 3 | left-both-right ankle jumps series | | |
| | | | | 4 | dips in landing position | | |
| | | | | 5 | landing on different soft grounds | | |
| | | | | 6 | single leg balance lunges | | |
| | | | | 7 | jumps on small surface | | |
| | | | | 8 | single leg springboard jumps | | |
| III | | C | **Tabata**<br>- 20" high intensity<br>- rest for 10"<br>- complete 8 stations<br>- rest for 2'<br>- repeat once | 1 | reactive single leg jumps from different heights (left) | Strengthening and conditioning of lower leg muscles. Postural control and stability. | Duration: max. 60' (incl. Warm-up)<br>Focus: Balance and upper body exercises (e.g.):<br>- Handstand exercises<br>- Hand stand exercises<br>- Cart wheel excises<br>- Intensive stretching (min. 20') |
| | | | | 2 | reactive single leg jumps from different heights (right) | | |
| | | | | 3 | single leg lunges | | |
| | | | | 4 | lunges against resistant band | | |
| | | | | 5 | reactive jumps from different heights | | |
| | | | | 6 | jump variation on a soft ground | | |
| | | | | 7 | ankle dips | | |
| | | | | 8 | lunges on a soft ground | | |
| IV | | D | **Circuit**<br>- 20' reps moderate intensity<br>- rest for 10"<br>- complete 8 stations<br>- rest for 2'<br>- repeat once | 1 | roll from the box into landing position | Postural control and stability. Flexible availability of motor adaptation to different surfaces. | Duration: max. 60' (incl. Warm-up)<br>Focus: Balance and upper body strength<br>Exercises (e.g.):<br>- Balance parcour<br>- Cross obstacles on the small surfaces (e.g. balance beam)<br>- Freezing on instable grounds<br>- Upper body circle training (min. 20') |
| | | | | 2 | singe leg hurdle jumps | | |
| | | | | 3 | left-both-right ankle jumps series | | |
| | | | | 4 | variation of turning jumps | | |
| | | | | 5 | landing on different soft grounds | | |
| | | | | 6 | single leg balance lunges | | |
| | | | | 7 | jumps on small surface | | |
| | | | | 8 | single leg springboard jumps | | |
| V | | E | **Landing parcour**<br>- 20' reps moderate intensity<br>- rest for 10"<br>- complete 8 stations<br>- rest for 2'<br>- repeat once | 1 | island jumping (from box to box) | Flexible availability of motor adaptation to different surfaces. | Duration: max. 60' (incl. Warm-up)<br>Focus: Balance and upper body exercises (e.g.):<br>- Handstand exercises<br>- Hand stand exercises<br>- Cart wheel excises using obstacles<br>- Stretching |
| | | | | 2 | jumping on/off a bank | | |
| | | | | 3 | spring board island jumping | | |
| | | | | 4 | jump off the large box | | |
| | | | | 5 | Jumping on a soft ground | | |
| | | | | 6 | jump off the small box | | |
| | | | | 7 | stair jumping | | |
| | | | | 8 | mini trampoline jumping | | |

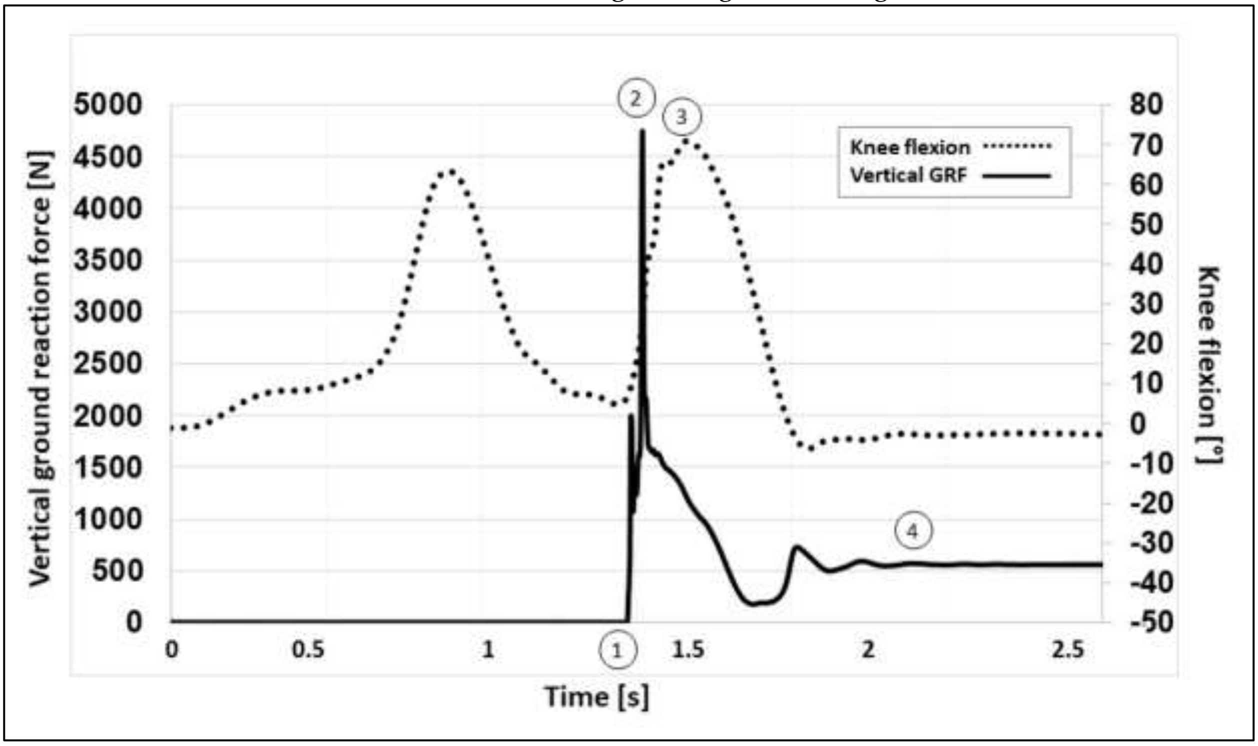
**Note:** Video references refer to video tutorials that are available on https://kielmotionlab.com/landungstraining/. Both, training and control group did the concurrent training.

All participants were provided with the same instructions. Specifically, after receiving the start signal, the participant stepped from the plateau, starting with the self-reported dominant foot (Christoforidou et al., 2017; McNitt-Gray, 1993; Sigward, Havens & Powers, 2011; Verniba et al., 2017) and performed a bilateral landing. The landing was repeated three times to help the participants familiarize themselves with the procedure. Contrary to the current recommendation to analyze Ground reaction force data from at least four repetitive measurements (James, Hermann, Dufek & Bates, 2007), only the third landing was analyzed in this study in order to ensure proximity to a competitive scenario. After the participants reached the final landing position, they remained until a second signal and left the force plate. The landings were repeated if the participant initially jumped upwards instead of stepping forward and after unsafe or unilateral landings (Christoforidou et al., 2017; McNitt-Gray, 1993). Both types of failures were visually identified by the investigator. A rest period of at least 30seconds was allowed between repetitions (Kuenze, Foot, Saliba & Hart, 2015).

### 2.4. Data analysis

Figure 1 gives an overview of the analyzed parameters, which included the maximum vGRF, the leg stiffness (knee flexion), and the time between ground contact and maximum knee flexion.

**Figure 1:** Representative graph of the resulting ground reaction forces and knee flexion values during landing from a height of 87cm




**Note:** The participant was a female gymnast (weight, 52kg). Marks identify (1) ground contact, (2) peak force, (3) maximum knee flexion, and (4) final landing position. vGRF, vertical ground reaction force.

Of the two peaks exhibited by the force curve during landing (Marinšek, 2010), the first is smaller and corresponds to the metatarsal head on the force plate, while the second is larger and corresponds to the landing of the heel. In this study, the last peak of the force curve was considered as the maximum vGRF, which was normalized to the body weight (BW) (McNitt-Gray, 1993) to allow comparison between participants. Therefore, vGRF values are given in BW.

The maximum value of knee flexion after ground contact was identified using an in-house MATLAB routine (Math Works, Natick, MA, USA). In this context, standing upright with legs straight (in the t-pose) was defined to correspond to 0° knee flexion. The braking time was defined as the time between ground contact and maximum knee flexion.

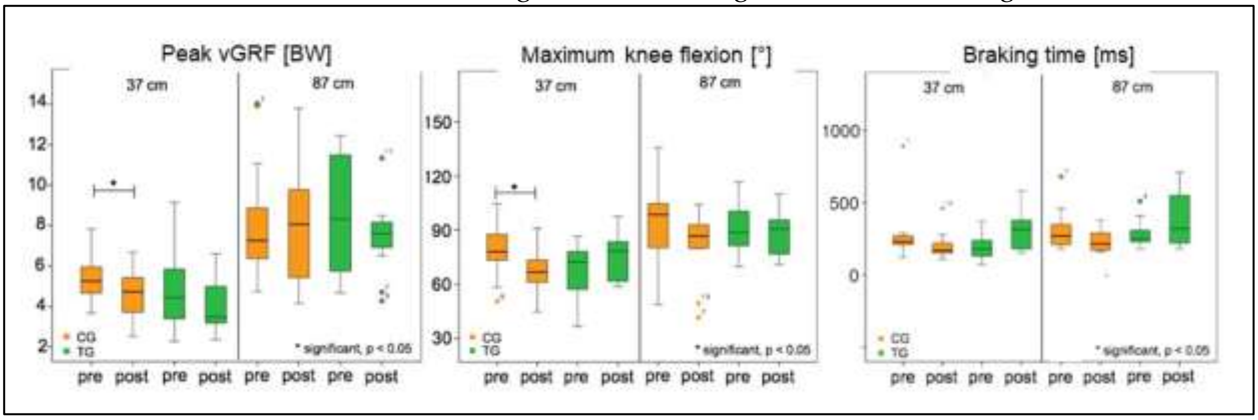
For each variable, the normality of the distribution was tested using the Shapiro-Wilk-Test. Since not all variables had normally distributed data, the significance of pre-post differences was evaluated using the Wilcoxon test for dependent samples. Statistical significance was established at $p<0.05$ and evaluated with regard to effects size (d) ranges (Cohen, 1992) of trivial (0–0.19), small (0.20–0.49), medium (0.50–0.79) and large (0.80 and higher). The relationship between the magnitude of change (Δ) in the variable of interest, the group affiliation, and the baseline value of the variable of interest was modeled using multivariate, linear regression (stepwise modeling). The corrected coefficient of determination ($R^2$) was calculated as a measure of the influence of the independent variable (training intervention, baseline value) on the variance of the dependent variables (knee flexion, peak force). The direct relationship between the dependent variables and the independent variables was examined by Spearman's correlation analysis.

## 3. Results

All 28 participants completed the study and conducted both measurement time points pre-post measurements. First, the group means for the variables of peak force, maximum knee flexion, and braking time before and after the study were examined for between-group differences. Data were analyzed separately for landings from heights of 37 and 87cm (Figure 2).

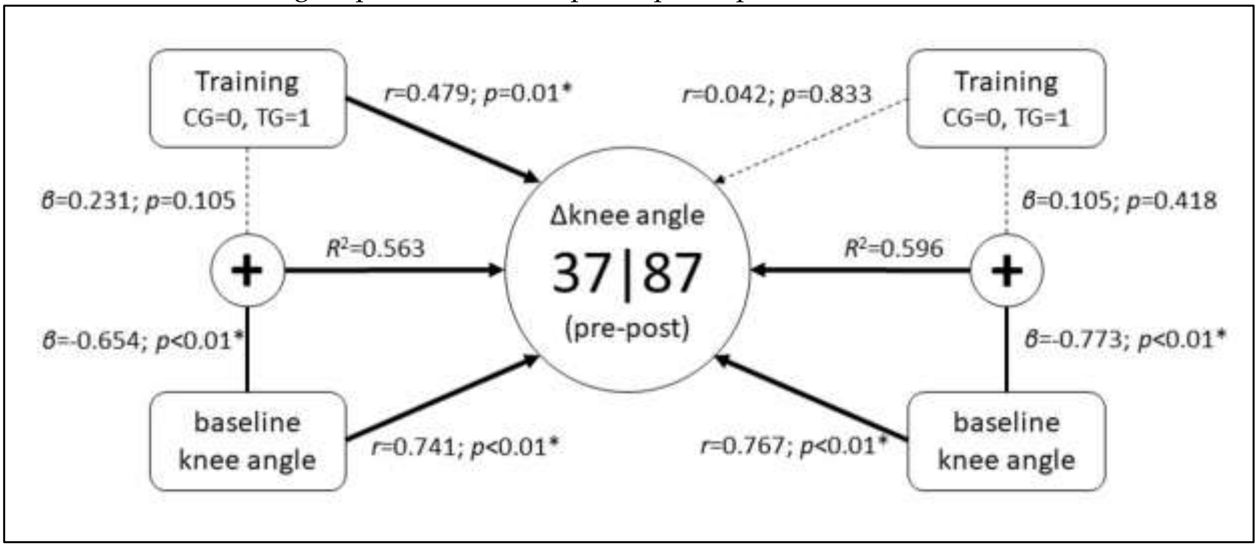
A significant pre-post difference, corresponding to a reduction in peak vGRF by 0.6 BW (median: 5.3±1.2 vs. 4.7±1.2BW; d=0.6), was found only for CG gymnasts, and only for landings from a height of 37cm. No other significant pre-post differences in vGRF means were found for either group or jump height. Of note, the variance of vGRF for landings from a height of 87cm reduced substantially in the TG (interquartile range: 7.8 vs. 1.4BW). The maximum knee flexion changed in the CG for landings from a height of 37cm, with significantly less knee flexion noted after the training (median: 78.0±13.7° vs. 66.7±12.7°; $p<0.05$; d=0.7). No other significant changes were found related to knee flexion or braking time (Table 1).

**Figure 2:** Effect of systematic landing training on ground reaction force, knee flexion, and braking time for landings from different heights




**Note:** The participants, who were beginner gymnasts, were randomly allocated to the training group (TG, green, n=14, 5-week program focused on landing training) or control group (CG, orange, n=14, no intervention). Values were obtained before and after the 5-week study (pre and post, respectively). Outliers are labeled with the participant ID. Body weight (BW); Vertical ground reaction force (vGRF).

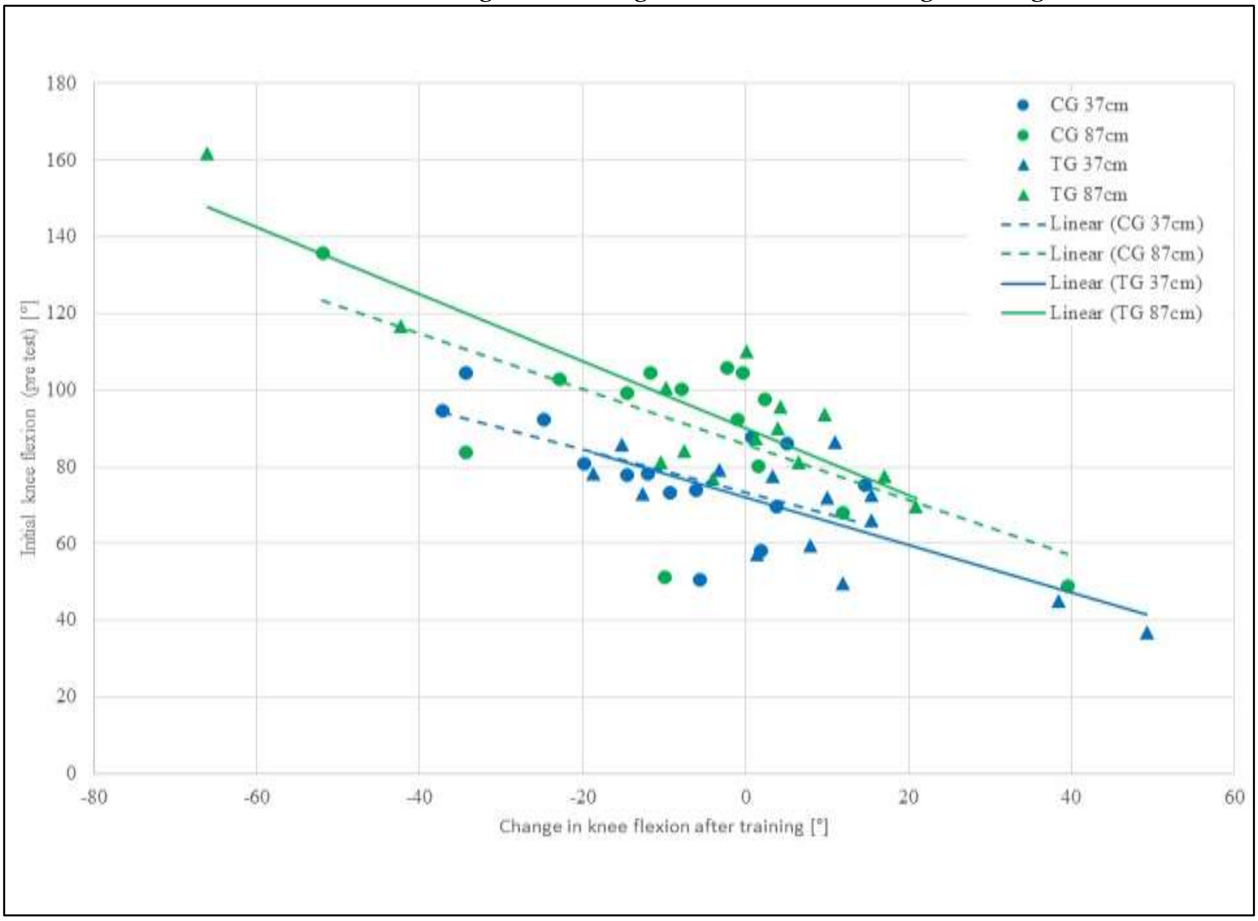
**Figure 3:** Relationship of pre-post changes in knee flexion with group affiliation and participant-specific baseline values




**Note:** Beginner gymnasts were randomly allocated to the training group (TG, n=14, 5-week program focused on landing training) or control group (CG, n=14, no intervention). Landings from heights of 37cm (left side) and 87cm (right side) were evaluated. The variance was evaluated using linear regression ($R^2$). Direct correlations were calculated using Spearman's analysis. Pre-post changes show significant (solid lines) correlation with baseline values.

The linear regression analysis shows that individual differences explain the intra-group variance of maximum knee flexion in the TG with 56% for landings from 37cm ($R^2$=0.563) and with 60% for landings from 87cm ($R^2$=0.596) (Figure 3). Only the baseline values of knee flexion (37cm: β=-0.654, p>0.01; 87cm: β=-0.773, p<0.01) made a significant contribution. Moreover, the baseline values correlated with the pre-post change in knee flexion for landings from both heights (37cm: r=-0.741; 87cm: r=-0.767; both with p<0.01), which indicates that participants with an initially large deviation from the target position also made a large progress throughout the landing training (Figure 4). The group affiliation, however, made only for landings from a height of 37cm a significant contribution to the change in knee flexion (r=0.479).

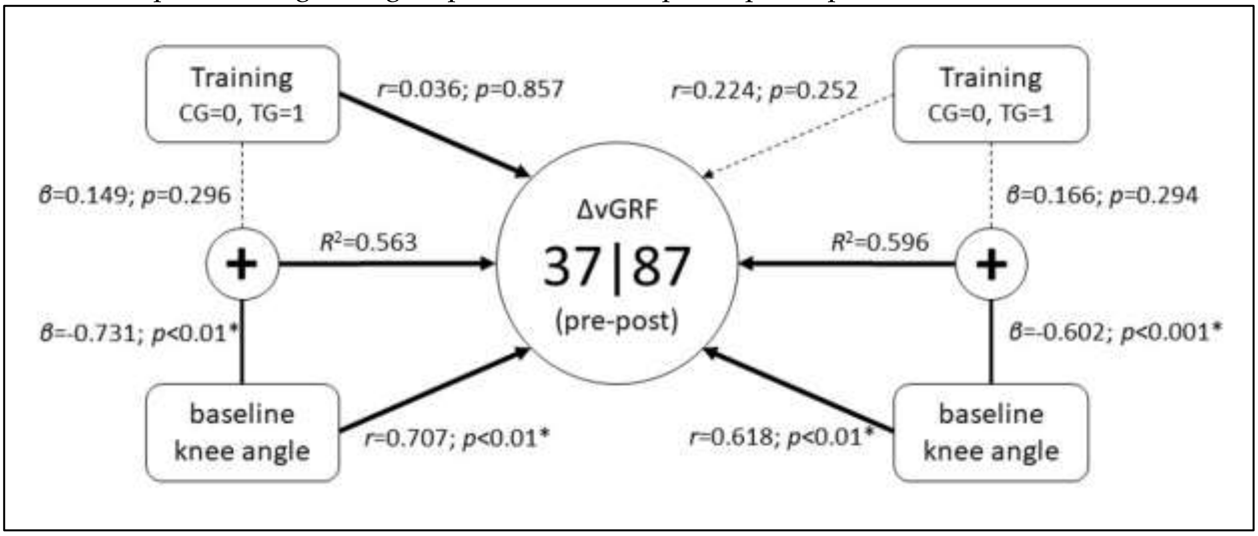
**Figure 4:** Correlation between baseline values and changes in maximum knee angle following five weeks of landing training




**Note:** The high correlation suggests that participants with high deviations from the target knee flexion upon landing (<90°) made the greatest progress over the 5-week training period.

The change in peak vGRF (Figure 5) was significantly correlated with the baseline values for landings from both heights (37cm: $\beta$=-0.731, p>0.01; 87cm: $\beta$=-0.602, p=0.001), explaining 48% (37cm) and 29% (87cm) of the variance within the TG. Additionally, baseline vGRFs correlated significantly (37cm: r=-0.707; 87cm: r=-0.618; both with p<0.01) with the participant-specific changes in peak vGRFs.

**Figure 5:** Relationship of pre-post changes in peak ground reaction force upon landing with group affiliation and participant-specific baseline values




**Note:** Beginner gymnasts were randomly allocated to the training group (TG, n=14, 5-week program focused on landing training) or control group (CG, n=14, no intervention). Landings from heights of 37 and 87cm were evaluated. The variance was evaluated using linear regression ($R^2$). Direct correlations were calculated using the Spearman method. Pre-post changes show a significant (solid lines) correlation with baseline values.

No significant effects were found for group affiliation, neither for the vGRF (F=0.268, p=0.614) nor the knee flexion (F=0.038, p=0.848). While the factor time point (pre- and post-measurement) had no significant effect on the knee flexion (F=1.867, p=0.195), it affected the vGRF (F=5.748, p=0.032) significantly. The height significantly affected the vGRF (F=57.798, p<0.05) and the knee flexion (F=63.688, p<0.05).

## 4. Discussion

In this study, we hypothesized that a systematic 5-week training of the availability of appropriate responses to unexpected landing situations and finishing in the final landing position defined by the FIG (2013) would result in lower vertical ground reaction forces and lesser knee flexion for both drop jump heights. After the training, the average magnitude of the vGRF was about four times BW from a height of 37cm, which corresponds to the results of Christoforidou et al. (2017), who analyzed trained subjects. We found higher vGRF (7.5BW) for landings from a height of 87cm. Assuming that the vGRF measured by Christoforidou et al. (2017) would linearly increase with a further increase in the plateau height, the vGRF from this study appears to be about 1 BW higher. To what extent this difference is due to the training level of the test subjects, remains to be investigated. However, only the CG showed a statistically significant pre-post change in peak vGRF, which reduced by 0.6BW); this change in peak vGRF was accompanied by switching to a stiffer landing technique, for which the CG did not train specifically. This result suggests that systematic landing training may not be necessary to achieve reduced vGRF, primarily since no changes were found in the TG. While the factor time significantly affects a reduction in vGRF over both groups, this training result is not related to group affiliation. Thus, this study shows that the familiarization with the landing setup, including a non-specific exercising, can already improve the landing technique. The braking times noted in this study are consistent with those reported previously (Christoforidou et al., 2017). The lack of significant pre-post change in braking time reflects the lack of change in knee flexion, which would correspond to braking distance.

On the other hand, systematic landing training had a significant effect on maximum knee flexion and vGRF (Figures 3 and 5) in those participants whose landing technique was poorer at baseline. In other words, the deviations from the defined landing position was corrected within only five weeks of training. Nevertheless, most participants landed close to the intended landing position even at baseline, which may explain the lack of between-group regarding knee flexion. This result suggests that, even without landing training, beginner gymnasts landed intuitively in the intended, stiff position. The analysis of adult beginners certainly plays a key role. Even the self-reported athletic biography let exclude that the test subjects have received any special landing training in the past, and their previous athletic activity did include extensive landings from the heights analyzed, a prove of correlation between the previous motor skills, and the training success is not possible. According to studies by McNair, and Prapavessis (1999) and Tillmann, Hass, Brunt, and Bennett (2004) it can only be assumed that court sports with higher proportions of sudden changes of direction and decelerations have already led to the development of advanced motor skills. The training aimed at strengthening the trunk and leg muscles. The extent to which this 5-week training protocol translated into muscle adaptation was not shown in this study. However, given the reduction in maximum vGRFs and consistent knee kinematics, it can be assumed that more optimal control of energy absorption through the musculature has been achieved (De Vita & Skelly, 1992; Kuenze et al., 2015). This assumption implies that muscle-tendon properties develop increased strength with training, which is fundamental for stiffness regulation during the braking phase (Christoforidou et al., 2017).

Several limitations of this study should be discussed. First, to simplify the implementation of motion analysis in the practical setting, we considered only one joint angle. However, this approach may be insufficient for adequately gauging the effects of training. Studies such as that conducted by Christoforidou et al. (2017) reported that, as beginner athletes gradually gain improved motor control, their ankle and hip angles during exercise change as well. In particular, the posture of the upper body during landing becomes more upright as the athletes develop advanced performance. Nevertheless, the knee angle is considered a key parameter for assessing the landing position and is used as the sole evaluation criterion of landing posture in competitions (Čuk & Marinšek, 2013; FIG, 2013). More complex motion analysis is warranted to clarify the effect of systematic landing training on landing kinematics in gymnasts.

Various studies have shown that the landing behavior of elite and novice gymnasts differs regarding muscle pre-activation (Christoforidou et al., 2017). This improvement in motor control could explain the change in vGRF noted in our study. It is expected that activated musculature has a higher capacity to compensate for the energy transmitted to the musculoskeletal system during landing.

## 5. Conclusion

In this study, we found that a 5-week landing exercise program was sufficient to correct extreme deviations of knee flexion from the desired stiff landing position. However, we could not confirm a significant effect of training (vGRF, knee flexion, braking time) in the overall TG, likely because baseline kinematics were already very good in this sample of beginner gymnasts. Consequently, we have to reject our hypothesis that 5-week training does not result in lower vertical ground reaction forces and higher knee angles for both drop jump heights. However, our present findings indicate that systematic landing training has the potential to induce positive muscle adaptation and improve motor control, which should be considered in further studies.

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**Conflicts of Interests**
The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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