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ORIGINAL ARTICLE

Effects of an 8-week physical exercise program on spinal manipulation biomechanical parameters in a group of 1st-year chiropractic students*

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Objective: To determine the effects of a physical exercise program on spinal manipulation (SM) performance in 1st-year chiropractic students.
Methods: One hundred and thirteen students from 2 chiropractic schools were assigned to 1 of 2 groups: exercise group (EG) for campus A students or control group (CG) (no training) for campus B students. All participated in 2 1-hour experimental training sessions that were added to the usual technique curriculum. At the beginning and at the end of each session, SM thrust duration and preload force release were recorded as dependent variables in 5 trials performed on a force-sensing table for a total of 10 recorded trials per session. The session consisted of several drills during which augmented feedback was provided to students to improve their skills. The EG performed physical exercises (push-ups, core stabilization, and speeder board exercises) 3 times per week for an 8-week period between the 2 training sessions.
Results: The mean thrust duration increased between the 2 sessions [+0.8 ms (±15.6)]. No difference between groups was found using a *t* test for independent samples ($p = .94$). The mean preload force release decreased between the 2 sessions (–6.1 N [±17.1]). Differences between groups were found using a *t* test for independent samples ($p = .03$); the results showed a reduction of preload force release in the participants in the EG group compared to those in the CG group (–8.1 N [±16.9] vs –0.3 N [±16.5]).
Conclusion: A physical exercise program seems to be beneficial in the SM learning process; chiropractic students should therefore be encouraged to do home physical exercises to develop their physical capabilities and improve SM delivery.

Key Indexing Terms: Chiropractic; Education; Exercise; Learning; Spinal Manipulation

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INTRODUCTION

Spinal manipulation (SM), defined as a specific form of joint manipulation, is characterized by a low-amplitude dynamic thrust of controlled velocity, amplitude, and direction.[1] It is considered a complex bimanual task requiring sensorimotor coordination and specific skills.[2] In order to perform SM safely and effectively, clinicians must master the ability to simultaneously control several biomechanical parameters, such as speed, force, amplitude, and duration of applied forces as well as body postures and complex bimanual motor skills to produce a thrust at a specific localization.[3] In some instances, more complicated SM maneuvers may require coordination of weight transfer, asymmetric postures, and significant muscular efforts all deployed while controlling patient positioning.[4]

SM performance and its related characteristics of expertise parameters have been studied over the past years. Several parameters, such as preload force, thrust duration, and thrust rate, were identified as indicators of performance in previous SM learning studies.[4–7] These parameters can usually be quantified using various force-sensing technologies, such as manikin, strength gauges, or force-sensing tables, which can provide the force-time profile of the executed SM.[8,9] Theoretically, a SM force-time profile is divided into 3 successive phases: the preload, thrust, and resolution.[10] During the preload phase, clinicians apply a progressive force to the target joint in order to identify the maximal physiological joint resistance at which the thrust should be applied.[3] During training, students are usually encouraged to identify by themselves

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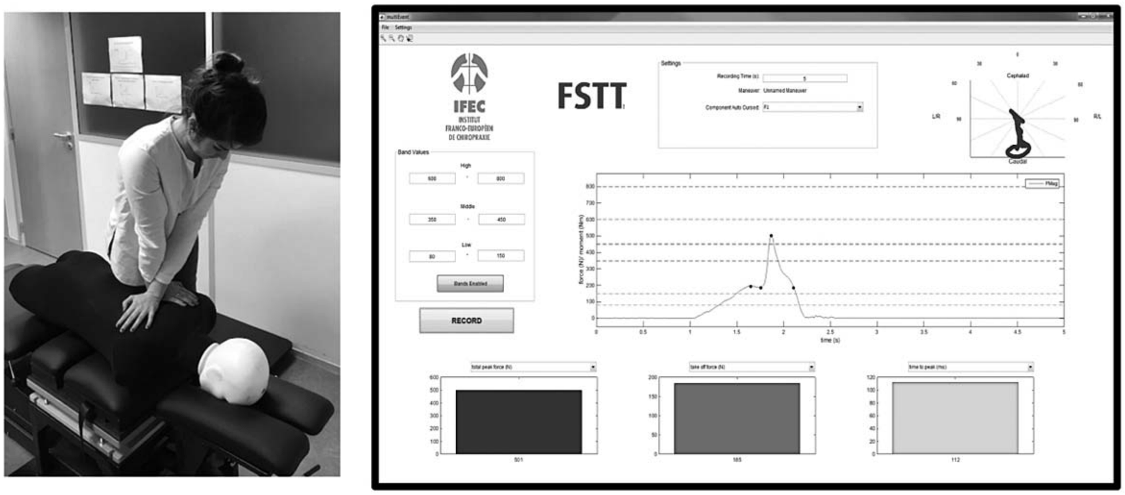

Figure 1 - Posterior-to-anterior thoracic spinal manipulation with high-velocity and low-amplitude technique and associated recorded data

the necessary force needed during preload but are also instructed to trigger the manual thrust without releasing the preload force. During the thrust phase, students are instructed to perform the thrust with the highest velocity possible while targeting a specific minimal peak force.

As indicated by Hurwitz,[11] the majority of SM in North America are administered by chiropractors. Indeed, the most common therapeutic tool used by chiropractors is the SM.[12] For this reason, chiropractic undergraduate programs dedicate a large part of their curriculum to teaching SM manual skills and clinical indications. SM teaching has considerably evolved over the past decade, and the application of motor learning principles within SM training courses has been shown to significantly impact the learning process.[4] Motor learning stems from 2 key ingredients: practice (repetition of SM) and associated feedback.[13] However, even though teaching strategies represent a crucial element in the learning process, the learners' background should also be considered as one of the most important determinants of motor learning.[14] Indeed, each learner has a different background, and intrinsic factors, such as physical capabilities, coordination skills, previous human movement experience, and levels of motivation, can all affect initial performances and the overall learning process.[14] As explained by Byfield and Barber,[3] chiropractic students must be trained to perform SM with a short time to peak force, and training should therefore include exercises that reinforce upper extremity muscles involved in the SM thrust phase (triceps, pectoralis major and minor, anterior deltoid, and serratus anterior). The authors also advocate the importance of daily exercise to improve cardiovascular fitness, strength, and flexibility as a global strategy to improve SM skill learning. Several studies have explored the relationship between health-related physical fitness and motor skills and found a positive association between these 2 variables.[15–18] However, there is currently no evidence linking physical capabilities improvement training and SM performance. The objective of the present study is therefore to determine whether an 8-week physical exercise program could impact the SM learning among 1st-year chiropractic students. It was hypothesized that students involved in the exercise program would present better improvement of thrust duration and preload force release.

METHODS

Participants

One hundred and thirteen 1st-year chiropractic students were recruited in 2 different campuses during the month of January 2017. They were assigned according to their campus to 1 of 2 groups: exercise group (EG) for campus A students or control group (CG) (no training) for campus B students. The 1st-year students had never had SM training prior to the beginning of the present study. Volunteers were excluded if they reported any injury/pain limiting their capacity to perform SMs. Each participant provided informed written consent, and the study was approved by the ethics committee of the Institut Franco-Européen de Chiropratique (certification no. CE 2017-08-25).

Experimental Procedure

The procedure consisted of 2 experimental feedback sessions separated by an 8-week period. The 2 feedback sessions were conducted similarly. First, a supervisor from each campus explained to the participants the posterior-to-anterior thoracic SM with the high-velocity and low-amplitude technique and the theoretical force-time profile of an SM (Figs. 1 and 2). The students were asked to perform a posterior-to-anterior thoracic SM with high velocity and low amplitude (Fig. 1). This technique was explained to the students by the 2 supervisors before the 1st feedback session. This SM was made using the double thenar technic.

After these explanations, the supervisors performed 1 good example of SM, 1 very slow trial (Fig. 3), and 1 last trial with a significant preload force release (Fig. 3). Then

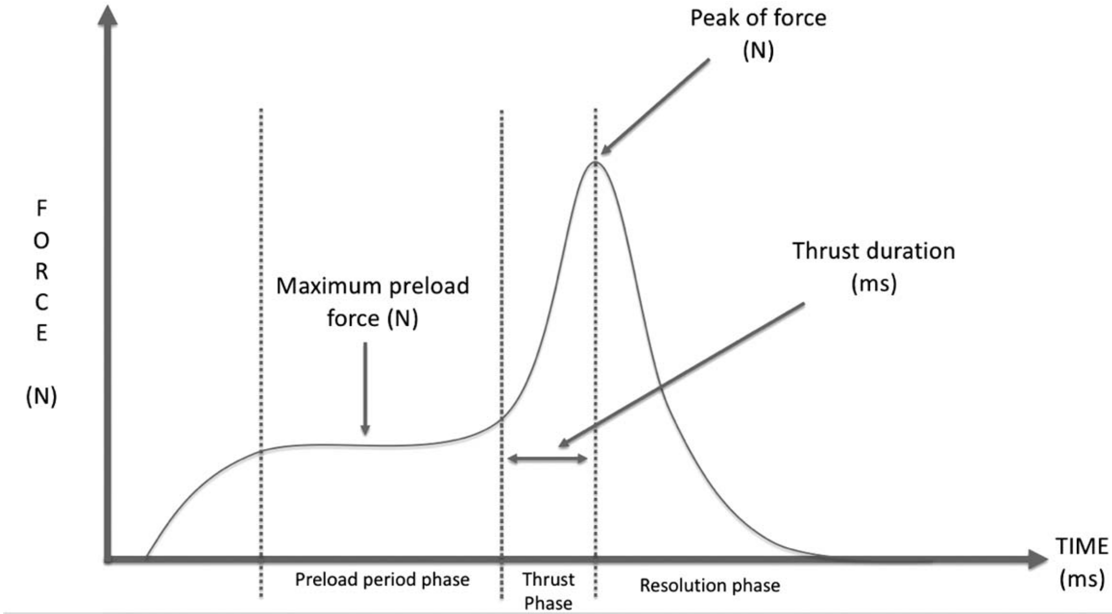

Figure 2 - Theoretical force-time profile of a spinal manipulation

each participant performed 3 familiarization trials of thoracic SM without force target on a manikin placed on a force-sensing table equipped with an AMTI force plate (Advanced Mechanical Technology Inc, Watertown, MA). While the students were performing these trials, verbal feedback was provided by the supervisors based on the thrust duration (time to peak force) and the preload force release.

Following this familiarization phase, a 1st assessment block of 5 SMs was performed by the participants without target force and without feedback. During the assessment blocks, the values of SM thrust duration (time to peak force) and preload force release were recorded.

Once these data were collected, a 40-minute feedback phase was implemented before the 2nd recorded trials block. During this training, the students performed SMs with feedback based on preload force release (N) and time to peak force (ms). Finally, each participant completed a 2nd assessment block of 5 SMs without feedback at the end of the 1st session. Ten SMs were recorded per session and subsequently analyzed. The 2nd session, scheduled 8 weeks later with the same group of participants, was identical to the 1st one. To limit the possibility of instruction or encouragement bias, the supervisors of both campuses had a discussion and received a document with the instruction and procedure.

Intervention

The campus where the intervention was implemented was selected using the www.randomization.com website. This randomization method was preferred to a participant randomization in order to limit the contamination bias between participants of a same campus. The 2 schools had exactly the same curriculum. Between the 2 sessions, the candidates in CG did not receive any particular instruction in addition to the normal school activities, while the

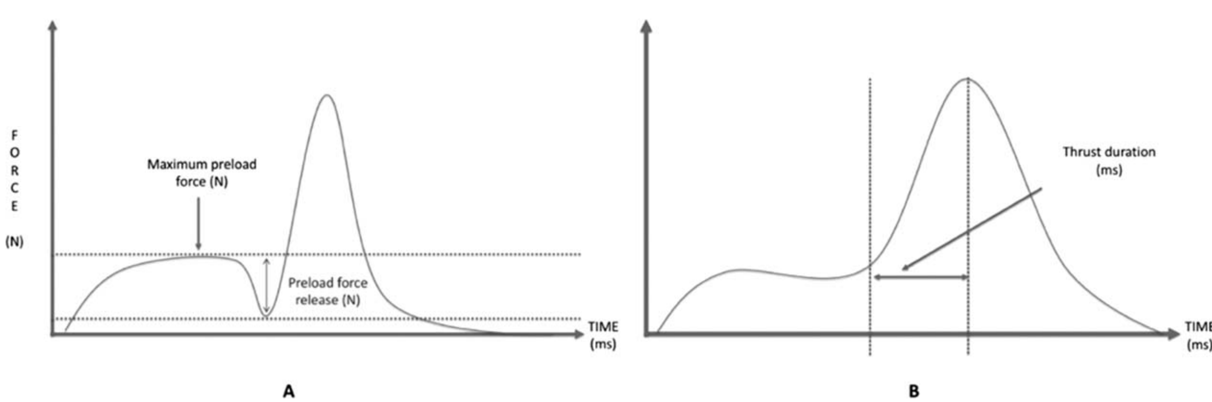

Figure 3 - (A) Spinal manipulation with a high preload force release. (B) Spinal manipulation with a slow time to peak force

Table 1 - Mean Values (SD) and Range of Thrust Duration

Thrust Duration (ms)	Session 1 Mean (SD) [Min–Max]	Session 2 Mean (SD) [Min–Max]
Whole sample (N = 113)	125.1 (19.3) [87.4–196.3]	126.0 (15.7) [89.4–176.6]
Exercise group (n = 84)	123.3 (18.1) [87.4–190.8]	124.4 (14.8) [89.4–159.2]
Control group (n = 29)	130.1 (21.8) [96.5–196.3]	130.8 (17.2) [104.9–167.6]

candidates of EG were given physical exercises: push-ups, core stabilization (prone plank), and repetition of SM on a table 3 times per week during the 8-week interval between the 2 training sessions. Push-up exercises were chosen because they involve both upper limb and trunk muscles.[19] The participants were asked to perform 3 repetitions of 10 push-ups on a stable surface. Core stabilization exercises consisted of maintaining the traditional prone plank as long as possible. The following description of the exercise was used, "Lie face-down with fists on the floor, feet shoulder width apart, and spine and pelvis in a neutral position. The elbows are spaced shoulder width apart directly below the glenohumeral joint. Lift the body up on the forearms and toes, keeping the body as straight as possible.[20]"

The last exercise consisted of 10 repetitions of SM on a hard surface and another 10 on a soft one. The goal of this exercise was to practice the SM movements as explained in the theoretical time-force profile.[10] Participants in the EG were asked to perform these 3 exercises 3 times per week.

Apparatus

SMs were applied on a manikin (H.A.M. series, CMCC, Toronto, ON, Canada) which was placed on a Leander 900 Z Series treatment table (Leader Health Technologies Corporation, Port Orchard, WA) with an embedded AMTI force plate (Advanced Mechanical Technology) to record the SM biomechanical parameters. Thrust duration (time to peak force) and preload force release were collected using force-sensing table technology. This tool has shown reliability and validity in measuring force loads during manipulations.[21] These forces transmitted to the bench can be analyzed in an xyz coordinate system using custom-made software (MATLAB, MathWorks, Natick, MA).

Data and Statistical Analysis

Force-time profiles were obtained for each 10 repetitions of the SMs during the 2 sessions. The force-time profile was analyzed to determine, for each test, the thrust duration (ms) and the preload release (N). Thrust duration is defined as the time between the beginning of the thrust and the maximum peak force.[22] Preload force release is the difference between the maximum preload force and the force recorded at the beginning of the thrust.[22] Means and standard deviations were calculated for the 10 SMs to obtain data for sessions 1 and 2.

Descriptive statistics were used to present the sample characteristics. Age and sex homogeneity between groups were assessed by the Wilcoxon signed-rank test and the chi-square test, respectively. Normality of variables (thrust duration and preload force release) was assessed using the Kolmogorov-Smirnov test and visual inspection. If data were not normally distributed, differences between the recorded set data for sessions 1 and 2 were calculated to obtain, for each participant, the difference between the 10 SM trial mean from session 1 and the 10 SM trial mean from session 2. A t test for independent samples was used to assess between-group differences. All statistical analyses were computed with Statistica 10 (Statsoft, Tulsa, OK) with a level of significance set to $p = .05$.

RESULTS

Participants

A total of 113 students agreed to participate in the study, 84 in school A (99 invited) and 29 in school B (94 invited). These 2 groups were similar for sex (63% of girls in group A vs 62% in group B) ($p > .05$) but not for age ($p = .03$). Indeed, the participants in school B were younger than those in group A (mean ± SD: 19.3 ± 2.1 vs 20.4 ± 3.9). All 113 students participated in the 2 training sessions and were included in the analysis.

SM Biomechanical Parameters: Effect on Thrust Duration (Time to Peak Force)

As indicated in Table 1, mean ± SD of thrust duration for the whole sample is 125.1 ms (±19.3) at session 1 and 126.0 ms ± 15.7 at session 2. The mean thrust duration increased between the 2 sessions (+ 0.8 ms ± 15.6, min to max: −60.7 to +52.6). This trend was observed for both EG and CG (+ 0.9 ms ± 11.2, min to max: −37.3 to +27.5 vs + 0.7 ms ± 23.4, min to max: −60.7 to +52.6, respectively). The t test for independent samples highlighted no differences between the 2 groups on thrust duration changes ($p = .94$).

SM Biomechanical Parameters: Effect on Preload Force Release

As indicated in Table 2, mean ± SD of preload force release for the whole sample is 19.5 N (±15.9) at session 1 and 13.4 N (±14.2) at session 2. The mean preload force release decreased between the 2 sessions (−6.1 N ± 17.1, min to max: −57.9 to +29.1). A similar decrease was found for EG (−8.1 N ± 16.9, min to max: −57.9 to +25.6) but not for CG (−0.3 N ± 16.5, min to max: −37.5 to +29.3). The t test for independent samples highlighted significantly statistical differences between the 2 groups on preload release changes ($p = .03$).

Table 2 - Mean Values (SD) and Range of Preload Force Release

Preload Force Release (N)	Session 1 Mean (SD) [Min–Max]	Session 2 Mean (SD) [Min–Max]
Whole sample (*N* = 113)	19.5 (15.9) [0–68.9]	13.4 (14.2) [0–57.2]
Exercise group (*n* = 84)	19.4 (16.0) [0–66.7]	11.4 (12.3) [0–57.2]
Control group (*n* = 29)	19.7 (15.9) [0–68.9]	19.4 (17.6) [0–53.2]

DISCUSSION

The objective of the present study was to determine whether an 8-week physical exercise program could impact the SM learning among 1st-year chiropractic students based on thrust duration and preload force release variables. For thrust duration, no difference was found between the 2 groups, indicating that the exercise program did not yield significant improvement for this specific parameter. Statistically significant differences were found for the decrease of preload force release between the 2 groups, indicating that participants involved in a physical exercise program improved this parameter compared to participants in CG.

This is the 1st study that assesses the effect of a physical exercise program on thrust duration and preload force release. We chose a basic SM task (prone thoracic spine manipulation) and 2 simple biomechanical components of SM (thrust duration and preload force release) because the participants were considered to be novices with very limited SM skill development. Indeed, this procedure was chosen because the students could focus only on the SM force-time profile without spending too much energy or attention on manikin stabilization. Based on the Fitts and Posner model of psychomotor skills acquisition, the students involved in the present study were in the cognitive phase of learning[23,24] at the time of testing. It is also the reason that no instructions about force were provided to participants, so they could direct their attention on the force-time profile without focusing on specific force target or preload values. During this stage, learners conceptualize the task they want to do according to the theoretical model of SM. According to Byfield and Barber, thrust duration represents one of the main parameters of SM skills[3] for PA thoracic spine manipulations, and values for this specific parameter should range between 110 and 200 ms.[7,25–27] Theoretically, a skilled SM should have a specific thrust duration and no release between the maximum preload force applied and the trigger of the SM thrust. A preload force release can lead to the loosening of tissue tension under the hand and may result in a possible reduction of SM precision.[8]

For this study, it was hypothesized that exercise would decrease thrust duration. However, no difference between groups was observed. Moreover, the mean ± SD of the whole sample did not improve this parameter during the protocol. Indeed, the sample presents a mean of 125 ms ± 19.3 for session 1 and 126.0 ± 15.7 for session 2. However, it is difficult to interpret thrust duration data since increased force applied during SM will yield increased thrust duration, especially in trainees.

The 2nd hypothesis was that participants involved in the physical exercise program would present decreased preload force release at the 2nd evaluation. Comparing the results of the EG with the CG confirmed that trainees in the EG decreased their force preload release. As explained previously, SM is characterized by 3 successive phases: preload, thrust, and resolution. Triggering the thrust without preload force release requires both coordination and force stabilization. Indeed, during the preload phase, clinicians transfer the body weight over the contact point to reach the joint resistance at which the thrust should be applied.[3] Once this specific resistance is reached, clinicians trigger the thrust with a specific duration and magnitude. These 2 phases involve different muscular groups; during the preload phase, lower limb muscles and trunk muscles are recruited to shift the body weight, while upper limb muscles are used to perform the SM thrust. One could argue that the exercise program suggested in this study improved core stability and upper limb strength, leading to improvement (decrease) in the preload force release variable. Despite the lack of evidence on the effect of physical training on SM learning, some studies highlighted a positive association between health-related physical fitness and motor skills.[15–18] Miyake et al.,[28] in a randomized and controlled group study, showed that core exercises improve upper extremity dexterity by enhancing the trunk stabilization. Moreover, in childhood, physical exercise programs were shown to increase motor skills of children.[29,30]

Study Limitations

In the present study, only thrust duration and preload force release were analyzed. Indeed, no target of force was given to participants that induce variability in the thrust duration variable. Moreover, only 29 participants were recruited from campus B vs 84 from campus A. Recruitment on both sites was carried out by 2 different individuals and could have impacted the motivation to participate. Participants in EG may have been more motivated because of their active involvement, while participants in CG had only 2 extra SM learning sessions. Even if the training protocol was standardized, differences in instructions or encouragements between campuses cannot be ruled out. Future studies should retest our hypothesis with a randomization of individuals instead of campuses to make sure that the preload force release results are due to the protocol and not to instructions or encouragement given by the supervisors. Finally, the exercise program mixed both physical (core stability and push-up) and SM motor tasks (SM repetitions on hard and soft surfaces). It is therefore not possible to assert which part of this program boosts the SM learning process, the physical capabilities, or the repetition.

CONCLUSION

A physical exercise program may be beneficial for the SM learning process. More research is needed to confirm that chiropractic students should be encouraged to do home physical exercises to develop their physical capabilities. Future research projects should evaluate the students' physical capabilities level at inclusion and then after the exercise protocol in order to find out if there is a correlation between changes in physical capabilities and biomechanical parameters of SM evolution.

FUNDING AND CONFLICTS OF INTEREST

This work was funded internally. The authors have no conflicts of interest to declare relevant to this work.

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Author Contributions

Concept development: AL, MD, YA, MP, FBC. Design: AL, MD, YA, MP, FBC. Supervision: AL, MD. Data collection/processing: AL, FBC, YA, MP. Analysis/interpretation: AL, MP, FBC, MD. Literature search: AL, FBC, YA, DG, MP, MD. Writing: AL, MD, YA, MP, FBC. Critical review: MP, MD.

REFERENCES

1. Bergmann TF, Peterson DH. Chiropractic Technique. 3rd ed. St Louis, MO: Mosby; 2010.
2. Haldeman S. *Principles and Practice of Chiropractic*. Norwalk, CT: Appleton & Lange; 1992.
3. Byfield D, Barber M. Chiropractic Manipulative Skills. 2nd ed. Edinburgh: Elsevier/Churchill Livingstone; 2005.
4. Triano JJ, Descarreaux M, Dugas C. Biomechanics—review of approaches for performance training in spinal manipulation. *J Electromyogr Kinesiol*. 2012; 22(5):732–739. doi: 10.1016/j.jelekin.2012.03.011.
5. Loranger M, Treboz J, Boucher JA, et al. Correlation of expertise with error detection skills of force application during spinal manipulation learning. *J Chiropr Educ*. 2016;30(1):1–6. doi: 10.7899/jce-15-4.
6. Descarreaux M, Dugas C, Treboz J, et al. Learning spinal manipulation: the effect of expertise on transfer capability. *J Manipulative Physiol Ther*. 2015;38(4): 269–274. doi: 10.1016/j.jmpt.2015.02.001.
7. Descarreaux M, Dugas C, Raymond J, et al. Kinetic analysis of expertise in spinal manipulative therapy using an instrumented manikin. *J Chiropr Med*. 2005; 4(2):53–60. doi: 10.1016/s0899-3467(07)60114-1.
8. Downie AS, Vemulpad S, Bull PW. Quantifying the high-velocity, low-amplitude spinal manipulative thrust: a systematic review. *J Manipulative Physiol Ther*. 2010;33(7):542–553. doi: 10.1016/j.jmpt.2010.08.001.
9. Stainsby BE, Clarke MC, Egonia JR. Learning spinal manipulation: a best-evidence synthesis of teaching methods. *J Chiropr Educ*. 2016;30(2):138–151. doi: 10.7899/jce-15-8.
10. Herzog W. The biomechanics of spinal manipulation. *J Bodyw Mov Ther*. 2010;14(3):280–286. doi: 10.1016/j.jbmt.2010.03.004.
11. Hurwitz EL. Epidemiology: spinal manipulation utilization. *J Electromyogr Kinesiol*. 2012;22(5):648–54. doi: 10.1016/j.jelekin.2012.01.006.
12. Beliveau PJH, Wong JJ, Sutton DA, et al. The chiropractic profession: a scoping review of utilization rates, reasons for seeking care, patient profiles, and care provided. *Chiropr Man Therap*. 2017;25:35. doi: 10.1186/s12998-017-0165-8.
13. Schmidt RA. A schema theory of discrete motor skill learning. *Psychol Rev*. 1975;82(4):225–260. doi: 10.1037/h0076770.
14. Schmitt RA, Wrisberg GA. *Motor Learning and Performance: A Situation-Based Learning Approach*. Champaign, IL: Human Kinetics; 2008.
15. Stodden DF, True LK, Langendorfer SJ, et al. Associations among selected motor skills and health-related fitness: indirect evidence for Seefeldt's proficiency barrier in young adults? *Res Q Exerc Sport*. 2013;84(3):397–403. doi: 10.1080/02701367.2013.814910.
16. Stodden D, Langendorfer S, Roberton MA. The association between motor skill competence and physical fitness in young adults. *Res Q Exerc Sport*.

2009;80(2):223–229. doi: 10.1080/02701367.2009.10599556.

17. Cattuzzo MT, Dos Santos Henrique R, Re AH, et al. Motor competence and health related physical fitness in youth: a systematic review. *J Sci Med Sport*. 2016;19(2):123–129. doi: 10.1016/j.jsams.2014.12.004.
18. Gouvea MA, Cyrino ES, Valente-Dos-Santos J, et al. Comparison of skillful vs. less skilled young soccer players on anthropometric, maturation, physical fitness and time of practice. *Int J Sports Med*. 2017;38(5):384–395. doi: 10.1055/s-0042-122815.
19. Freeman S, Karpowicz A, Gray J, et al. Quantifying muscle patterns and spine load during various forms of the push-up. *Med Sci Sports Exerc*. 2006;38(3):570–577. doi: 10.1249/01.mss.0000189317.08635.1b.
20. Schoenfeld BJ, Contreras B, Tiryaki-Sonmez G, et al. An electromyographic comparison of a modified version of the plank with a long lever and posterior tilt versus the traditional plank exercise. *Sports Biomech*. 2014;13(3):296–306. doi: 10.1080/14763141.2014.942355.
21. Rogers CM, Triano JJ. Biomechanical measure validation for spinal manipulation in clinical settings. *J Manipulative Physiol Ther*. 2003;26(9):539–548. doi: 10.1016/j.jmpt.2003.08.008.
22. Cohen E, Triano JJ, McGregor M, et al. Biomechanical performance of spinal manipulation therapy by newly trained vs. practicing providers: does experience transfer to unfamiliar procedures? *J Manipulative Physiol Ther*. 1995;18(6):347–352.
23. Fitts PM, Posner MI. *Human Performance*. Belmont, CA: Brooks/Cole; 1967.
24. Dunphy BC, Williamson SL. In pursuit of expertise. Toward an educational model for expertise development. *Adv Health Sci Educ Theory Pract*. 2004;9(2):107–127. doi: 10.1023/B:AHSE.0000027436.17220.9c.
25. Herzog W, Kats M, Symons B. The effective forces transmitted by high-speed, low-amplitude thoracic manipulation. *Spine (Phila Pa 1976)*. 2001;26(19):2105–2110.
26. Descarreaux M, Dugas C. Learning spinal manipulation skills: assessment of biomechanical parameters in a 5-year longitudinal study. *J Manipulative Physiol Ther*. 2010;33(3):226–230. doi: 10.1016/j.jmpt.2010.01.011.
27. Starmer DJ, Guist BP, Tuff TR, et al. Changes in manipulative peak force modulation and time to peak thrust among first-year chiropractic students following a 12-week detraining period. *J Manipulative Physiol Ther*. 2016;39(4):311–317. doi: 10.1016/j.jmpt.2016.02.010.
28. Miyake Y, Kobayashi R, Kelepecz D, et al. Core exercises elevate trunk stability to facilitate skilled motor behavior of the upper extremities. *J Bodyw Mov Ther*. 2013;17(2):259–265. doi: 10.1016/j.jbmt.2012.06.003.
29. Gallotta MC, Emerenziani GP, Iazzoni S, et al. Effects of different physical education programmes on children's skill- and health-related outcomes: a pilot randomised controlled trial. *J Sports Sci*. 2017;35(15):1547–1555. doi: 10.1080/02640414.2016.1225969.
30. Nobre GG, de Almeida MB, Nobre IG, et al. Twelve weeks of plyometric training improves motor performance of 7- to 9-year-old boys who were overweight/obese: a randomized controlled intervention. *J Strength Cond Res*. 2017;31(8):2091–2099. doi: 10.1519/jsc.0000000000001684.