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# **Exploratory investigation of impact loads during the forward handspring vault**

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27 **Abstract**

28           The purpose of this study was to examine kinematic and kinetic differences in low and high  
29 intensity hand support impact loads during a forward handspring vault. A high-speed video camera  
30 (500 Hz) and two portable force platforms (500 Hz) were installed on the surface of the vault table.  
31 Two-dimensional analyses were conducted on 24 forward handspring vaults performed by 12 senior  
32 level, junior Olympic program female gymnasts ( $16.9 \pm 1.4$  yr; body height  $1.60 \pm 0.1$  m; body mass  
33  $56.7 \pm 7.8$  kg). Load intensities at impact with the vault table were classified as low (peak force <  
34  $0.8 \times$  body weight) and high (peak force  $> 0.8 \times$  body weight). These vaults were compared via  
35 crucial kinetic and kinematic variables using independent t-tests and Pearson correlations.  
36 Statistically significant ( $p < 0.001$ ) differences were observed in peak force ( $t_{(24)} = 4.75$ , ES = 3.37)  
37 and time to peak force ( $t_{(24)} = 2.07$ , ES = 1.56). Statistically significant relationships between the  
38 loading rate and time to peak force were observed for high intensity loads. Peak force, time to peak  
39 force, and a shoulder angle at impact were identified as primary variables potentially involved in the  
40 determination of large repetitive loading rates on the forward handspring vault.

41 **Keywords:** Upper extremity loading, gymnastics, kinetics, kinematics, injury.

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57 **Introduction**

58           Gymnastics is somewhat unique in that the athletes actually ‘jump’ from their hands as well  
59 as their feet. Clearly, jumping from one’s hands is more difficult and places extraordinary demands  
60 on limbs that were designed for reaching and grasping rather than jumping and landing. The  
61 inherent problem of using the upper extremities for jumping and landing has been recognized for  
62 some time in gymnastics (Beunen et al., 1999; Di Fiori et al., 2006).

63           In 2001, the International Gymnastics Federation changed the vaulting apparatus in order to  
64 facilitate performance and safety in men’s and women’s artistic gymnastics. The replacement of the  
65 vaulting horse with the vaulting table has been one of the most significant modifications to  
66 influence gymnastics tactics and performance. The necessity for a new apparatus was related to an  
67 increasing incidence of injury (Sands et al., 2003). The vaulting table maintained the traditional  
68 competition top surface height (1.25m for women and 1.35m for men), however, it is characterized  
69 by a completely different shape, geometry, and elasticity properties. The shape has been described  
70 as a ‘tongue’ shape, with a 40% wider and three times longer top surface than the previous women’s  
71 vaulting horse apparatus. Moreover, the upper surface of the table is slightly inclined (about 5°).

72           The new vault table features listed above created numerous advantages for gymnasts. In  
73 particular, women gymnasts were able to benefit from a wider, longer and more visible surface thus  
74 reducing hand placement inaccuracy errors in the pre-flight phase (from a springboard to a vault  
75 table), improved confidence in the hand placement on the apparatus, and a softer and slightly elastic  
76 hand contact surface. The impact and push-off actions during the hand contact phase were thought  
77 to be enhanced by the changes provided by the vault table. Figure 1 shows typical forward  
78 handspring-style hand placement for an old vault horse and a current vault table. The table surface  
79 may enhance a wrist position by allowing a less severe hyper-extended position (Sands and  
80 McNeal, 2002).

81  
82           Figure 1 around here.

83  
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85           A discourse on gymnastics nearly always turns to injury and injury prevention. Injury  
86 remains the most serious problem for gymnastics (Sands, 2000). Epidemiologic studies of  
87 gymnastics injuries have often found the vaulting event to be ranked the highest in terms of injury  
88 incidence and severity (Caine et al., 2003), and the wrist has been shown to be particularly  
89 vulnerable in both acute and over-use injuries (De Smet et al., 1994; Liebling et al., 1995; Sands et  
90 al., 1993). However, since the introduction of the vaulting table the incidence of upper extremity  
91 injuries does not appear to have decreased (Webb and Rettig, 2008), in fact, between 70 and 80% of

92 the gymnasts still suffer from wrist injuries (Di Fiori et al., 2006). According to Singh et al. (2008),  
93 upper extremities account for 42% of the gymnastics injuries and handspring-type skills are most  
94 frequently associated with injuries. Although direct causation of wrist injuries associated only with  
95 vaulting is difficult to demonstrate due to the multi-event nature of women's gymnastics, it is  
96 common to observe gymnasts performing their vaults with taped wrists or wearing protective wrist  
97 braces, and often train and compete with wrist pain (Beunen et al., 1999). An excessive loading  
98 pattern may also contribute to injuries at other locations such as an elbow, a shoulder and a neck  
99 (Sands et al., 1993; Wadley and Albright, 1993). For instance, indirect forces transmitted through  
100 outstretched and abducted arms (e.g., catching oneself from a forward fall to the hands) can drive  
101 the head of the humerus posteriorly and result in a posterior dislocation of the shoulder (Whiting  
102 and Zernicke, 1998). It has been suggested that upper extremity injuries such as sprains, strains,  
103 contusions, tendonitis, and bursitis are due to intense compressive loads generated at the hands  
104 during repetitive hand support impacts (Nattiv and Mandelbaum, 1993; Werner and Plancher,  
105 1998).

106 A preliminary investigation on two-dimensional kinetic data collected from direct  
107 measurement during the contact phase of the gymnasts' hands with the vault table showed possible  
108 injury-related factors (Penitente et al., 2010). Thus, the present study may find a rationale for  
109 urgency in understanding how the magnitude of hand support impact forces and accompanying  
110 kinematics may be linked to upper extremity trauma. Results from this study may also provide  
111 preliminary information that will assist physiotherapists and orthopaedists in return-to-activity  
112 decisions.

113 The main purpose of the present exploratory study was to test the hypothesis that the impact  
114 events with the table that were characterized as high intensity (HI, forces with impact peaks  $> 0.8$   
115 body weight (BW)) were associated with potential upper extremity injury risk factors. We also  
116 hypothesized that associated risk factors were: shorter time to impact peak force, a larger loading  
117 rate, a greater impulse load, greater wrist hyperextension, greater shoulder extension angles, and a  
118 greater centre of mass vertical velocity at hand contact. In addition, we hypothesized that the  
119 variables above would contrast statistically with forward handsprings executed with low intensity  
120 (LI, forces with impact peaks  $< 0.8$  BW).

121

## 122 **Material and Methods**

### 123 *Participants*

124 Twelve level 10 junior Olympic national team female gymnasts with a mean age of  $16.9 \pm 1.4$   
125 yr, body height of  $1.60 \pm 0.1$  m and body mass of  $56.7 \pm 7.8$  kg volunteered for this study. USA  
126 gymnastics classifies these gymnasts immediately below the international competitive levels.

127 Gymnasts provided informed consent and ethical approval was granted in accordance with the  
128 United States Olympic Committee policies on research at the United States Olympic Training  
129 Center.

130

### 131 *Measures*

132 A video camera (500 Hz, Photron 1280, Motion Engineering Company, USA) was positioned on  
133 the side of the table with its optical axis perpendicular to the direction of the movement. The  
134 recorded videos were scaled by means of a rectangular calibration frame measuring 1.00 x 1.10 m,  
135 used for two-dimensional (2D) kinematic analyses of eleven reflective markers (diameter 22.5 mm)  
136 (5<sup>th</sup> metatarsal joint, calcaneus, lateral malleolus, lateral condyle, greater trochanter, inferior lateral  
137 angle of the 12<sup>th</sup> rib, shoulder, lateral epicondyle, ulnar styloid, 5<sup>th</sup> metacarpal joint, and head). The  
138 markers were used to identify a nine-segment body model. Markers were digitized using Peak  
139 Motus™ 9.1 (Peak Performance Technologies, USA). The position of the calibration frame  
140 encompassed the space used by the gymnasts during the hand-table contact phase. Coordinates were  
141 smoothed using a Butterworth digital filter with frequency cut-off between 5 and 8 Hz.

142 The centre of mass (CM) was calculated using the Kjeldsen's model of female gymnasts  
143 (Plagenhoef, 1971). The orientation of the 2D system had the x-axis aligned along the main  
144 horizontal direction of movement and the z-axis aligned vertically. The following kinematic  
145 variables were selected: a wrist angle, a shoulder angle and CM horizontal and vertical velocities at  
146 hand-table impact. The wrist joint angle was identified as the relative angle in the sagittal plane of  
147 the forearm and the hand segments (the wrist angle of 180° corresponded to a position with the  
148 forearm and hand aligned; Figure 1); the shoulder angle was identified as the anterior relative angle  
149 in the sagittal plane of the trunk and the upper arm segments (the shoulder angle of 180°  
150 corresponded to a position with the trunk and upper-arm aligned).

151

### 152 *Procedures*

153 The vault table surface was equipped with two portable force platforms 37 x 37 x 4.5 cm  
154 (Pasco Scientific, USA) fixed to a rigid wooden foundation base. The force platforms were covered  
155 with a thin mat to ensure cushion and traction during hand contact (0.4 cm) and the edges of the  
156 force platforms were designated by taped lines placed on top of the thin mat surface to provide  
157 visual targets for the gymnasts' hand placements (Figure 2a). The vault table was set at the  
158 women's competition height of 1.25m. Reaction forces generated during forward handspring vaults  
159 were measured in the vertical (Z) and anterior-posterior (X) planes at a rate of 500 Hz. The  
160 accuracy of each force platform mounted on a rigid wooden foundation was calibrated via static

161 linearity (both vertical and horizontal components), static regionality, and dynamic force-time  
162 comparisons against a laboratory force platform with known validity (Penitente et al., 2010).

163

164 Figure 2 around here.

165

166 Gymnasts participated in a self-selected warm up activity before performing a forward  
167 handspring vault landing feet-first on mats stacked to the level of the vault table (Figure 2b).  
168 Twenty-four successful trials were selected (two for each gymnast) including a simultaneous  
169 measurement of left and right hands from the two force platforms. In order to combine kinematic  
170 and kinetic variables only the 24 impact events recorded from the right hand were used for analysis.

171

### 172 *Statistical Analysis*

173 Forces were scaled to each gymnast's body mass. The following kinetic variables were  
174 investigated: impact (Fz) and braking (Fx) peak force magnitudes (BW), time from contact to  
175 vertical (Fz) and braking (Fx) peak force (s), a loading rate (from contact to impact peak force - Fz)  
176 ( $BW \cdot s^{-1}$ ) [24], a vertical impulse ( $BW \cdot s$ ), and a horizontal impulse ( $BW \cdot s$ ).

177 Based on the split median method, data were divided in two groups. The first group was  
178 formed by those forward handsprings that showed impact peak force magnitudes less than 0.8 BW  
179 (LI group), operationally defined as 'low intensity load'. The second group was determined by  
180 impact peak force greater than 0.8 BW (HI group), operationally defined as 'high intensity load'  
181 (Markolf et al., 1990) (Figure 3).

182

183 Figure 3 around here

184

185 Data analyses were performed with the software SPSS 18.0 (SPSS, Inc. Chicago, USA). The  
186 reliabilities between the two trials performed by each gymnast were assessed by intra-class  
187 correlation coefficients (ICCs) (alphas ranged from 0.26 to 0.85). Some variables indicated marked  
188 individual variances that were not always captured by the ICCs and some variables showed as high  
189 as 20% relative error between performance trials. Due to the exploratory nature of this study and in  
190 the attempt to maintain a degree of acknowledgement of a marked individual variability of the  
191 athlete performance, the trials variables were not collapsed to produce a single mean for each  
192 athlete. Moreover, the fact that such variability occurred is considered an important aspect of this  
193 study's data (Bates, 1996).

194

195 All the variables were tested for normality according to the Shapiro-Wilks procedure.  
196 Differences in kinetic and kinematic variables between HI and LI were assessed with the  
197 independent t-test using both trials for each gymnast ( $p < 0.05$ ). As both trials for each gymnast  
198 were used for analysis, the comparisons between HI and LI were tested using the method described  
199 by Gönen et al. (2001) that accounts for within subject clustering. Thus, the t statistic was divided  
200 by a correction factor defined as  $C = [1 + (m - 1)\rho]$ , where m is the number of trials for a gymnast  
201 and  $\rho$  is the intraclass correlation ( $\rho = \text{Variance between subjects} / \text{Variance between subjects} +$   
202  $\text{Variance within subjects}$ ). The Cohen's d effect size index was used to estimate the magnitude of  
203 significant differences between HI and LI groups (Cohen, 1988). Pearson's correlation ( $p < 0.05$ )  
204 was used to determine the relationships among the kinetic and kinematic variables.

205

## 206 **Results**

207 The force peak magnitude of the twenty-four trials indicated that twelve trials were LI impact  
208 load and twelve were HI impact load. The descriptive statistics relative to the kinetic and kinematic  
209 variables for LI and HI groups are presented in Table 1.

210 Table 1 around here.

211

212 Impact peak force ( $t_{(24)} = 4.75, p < 0.001$ ) and time to impact peak ( $t_{(24)} = 2.07, p < 0.001$ )  
213 were the only variables showing a statistically significant difference between HI and LI groups.  
214 Further, Cohen's d values (3.37 and 1.56, respectively) indicated a large effect size.

215 The HI group showed a statistically significant correlation between the time to impact peak  
216 and the loading rate ( $r = -0.78, p = 0.003$ ), the time to braking peak ( $F_x$ ) ( $r = 0.83, p = 0.001$ ), the  
217 CM horizontal velocity at hand impact ( $r = 0.82, p = 0.047$ ), and CM horizontal velocity with the  
218 wrist angle at hand impact ( $r = -0.63, p = 0.027$ ). The loading rate resulted in a statistically  
219 significant relationship with the time to braking peak force ( $r = -0.82, p = 0.001$ ) and the wrist angle  
220 at impact ( $r = 0.73, p = 0.007$ ). The braking peak force showed a statistically significant relationship  
221 with the horizontal impulse ( $r = -0.64, p = 0.024$ ). The shoulder angle at hand impact was  
222 significantly correlated with the wrist angle at the same instant of impact ( $r = 0.62, p = 0.032$ ).

223 The LI group showed a statistically significant correlation between the impact peak force  
224 and the loading rate ( $r = 0.67, p = 0.017$ ). The time to impact peak force and the CM horizontal  
225 velocity at impact were statistically correlated ( $r = 0.74, p = 0.006$ ). The time to braking peak force  
226 was statistically correlated with the horizontal impulse ( $r = -0.75, p = 0.005$ ). The shoulder angle at



227 hand impact showed a significant correlation with the time to braking peak force ( $r = -0.73$ ,  $p =$   
228  $0.007$ ) and with the horizontal impulse ( $r = 0.67$ ,  $p = 0.018$ ).

229

## 230 **Discussion**

231 This study was designed to investigate the intensity of impact loads obtained during the  
232 forward handspring vault performed by highly trained female gymnasts. Second, the study was  
233 aimed to determine the magnitudes and interactions among kinetic and kinematic variables that  
234 characterize hand-table impact events and duration with high and low intensity loads.

235 The magnitude of compressive impact, the loading rate (Nigg, 1985), the impulse, the  
236 angular position of the wrist and shoulder at hand support impact, and the centre of mass velocities  
237 have been identified as primary contributors to upper extremity trauma (Caine et al., 2003; De Smet  
238 et al., 1994; Liebling et al., 1995; Sands et al., 1993). The forward handspring skill was chosen as  
239 standard fundamental skill commonly used by coaches to develop higher scoring performances and,  
240 for research in safety issues.

241 Major findings indicated that the two intensity groups identified were characterized by  
242 statistically significant differences in impact peak force magnitude and time to impact peak force;  
243 however, no statistically significant differences in the overall loading rate were observed. The rate  
244 at which upper and lower extremities are loaded has been implicated in stress fractures and soft  
245 tissue dysfunctions (Nigg, 1985; Markolf et al., 1990; Seeley and Bressel, 2005). From an injury  
246 risk perspective, the results from the present study indicate that during the handspring vaults, the  
247 shock absorption demands placed on the upper extremities are high, particularly when extrapolated  
248 to dozens of daily repetitions.

249 This is the first study to directly measure the reaction forces during the hand support of a  
250 gymnastics vault. As there are no measurements of the impact loading rate associated with similar  
251 skills in the literature, a direct comparison of our results with other studies cannot be made.  
252 However, if we consider forward handspring skills as a particular `form of a take-off` or a `jump`  
253 that involves hands rather than feet, comparisons with lower extremity jump exercises can be made.  
254 Results by Richard and Veatch (1994) showed that loading rates of the lower extremities could be  
255 categorized as high during hopping-type jumps from different jumping heights. It is interesting to  
256 note that the loading rates observed for the forward handsprings with LI loads ( $68.2 \text{ BW}\cdot\text{s}^{-1}$ ) were  
257 greater than the loading rates produced during lower extremity drop jumps from a height of 6 cm  
258 ( $56.99 \text{ BW}\cdot\text{s}^{-1}$ ). The loading rate found for the HI load group ( $96.1 \text{ BW}\cdot\text{s}^{-1}$ ) was greater than the  
259 loading rate developed during a drop jump from a height of 8 cm ( $73.1 \text{ BW}\cdot\text{s}^{-1}$ ) (Richard and  
260 Veatch, 1994). The maximum loading rates recorded for both groups (LI =  $151.4 \text{ BW}\cdot\text{s}^{-1}$  and HI =  
261  $161.6 \text{ BW}\cdot\text{s}^{-1}$ ) were greater than that associated with each leg during a two-foot landing drop jump

262 from a height of 61 cm ( $136 \text{ BW}\cdot\text{s}^{-1}$ ) measured by Bauer et al. (2001). Moreover, in the HI load  
263 group in the present investigation, the impact peak force was characterized by magnitudes  
264 comparable with typical impact force generated during running at  $3 \text{ m}\cdot\text{s}^{-1}$  ( $1.6 \pm 0.4 \text{ BW}$ ) (Munro et  
265 al., 1987).

266 In upper extremity stretching-shortening-type motions such as the forward handspring, there  
267 are large and relatively unnatural ranges of impact loads similar in magnitude to the lower  
268 extremities; the risk of injury is obviously high (Markolf et al., 1990). The vertical forces observed  
269 during the present study in HI handspring vaults may be intense enough alone or in aggregate to  
270 cause injuries (such as distal radial syndrome, carpal stress fracture, capsulitis, positive ulnar  
271 variance and carpal instability) associated with weight-bearing gymnastics exercises in general  
272 (Gabel, 1998). Werner and Plancher (1998) reported that 90% of wrist injuries are related to  
273 compressive stress, and closely related to this type of stress is a loading rate (Markolf et al., 1990).

274 A comparison between the impact peak forces and loading rates measured in the present  
275 study with those measured by Roy et al. (1985) during two gymnastics tumbling skills, round-off on  
276 the floor (impact peak =  $2.2 \pm 0.3 \text{ BW}$ ; loading rate =  $19.2 \pm 4.6 \text{ BW}\cdot\text{s}^{-1}$ ) and round off on the  
277 vaulting springboard (impact peak =  $2.4 \pm 0.3 \text{ BW}$ ; the loading rate =  $28.6 \pm 6.7 \text{ BW}\cdot\text{s}^{-1}$ ). In the  
278 tumbling skills analysed by Roy et al. (1985), the higher impact loads in the round-off are  
279 associated with lower loading rates. In contrast, the present study shows that both intensity groups  
280 displayed high loading rate values during hand contact with similar CM velocities. These results  
281 contrast with the assumption that impact peak force and a loading rate are speed-dependent, as  
282 shown in running activities (Munro et al., 1987), it is not applicable to handspring vault hand  
283 support skills. In addition, the premise that high impact forces accompany high loading rates in  
284 jumping movements (McNitt-Gray, 1991) is not similarly associated with vault handspring skills. In  
285 fact, this study showed that low impact peak forces may produce high loading rates. This was  
286 supported by the absence of a significant correlation between hand-table impact peak forces and  
287 loading rates.

288 For the HI group, the loading rate was related to the time to vertical peak force. A short time  
289 to peak force ( $0.007 \pm 0.003 \text{ s LI}$ ;  $0.016 \pm 0.008 \text{ s HI}$ ) appeared to be more likely a crucial factor in  
290 generating high loading rates and thereby may be related to injury potential. A similar finding was  
291 reported by Dixon and Kerwin (1999) in their study on the influence of a heel lift on the Achilles  
292 tendon load during running. It is important to consider that the time to impact peak is related to  
293 muscle pre-activation which is used to control and attenuate or accentuate impact loading (Nigg,  
294 1985). It has been shown that subjects' ability to prepare their bodies for shock absorption depends  
295 on factors such as time, segment kinematics, tissue compressibility and elasticity, and vision  
296 preceding the impact. It was suggested that these components can affect muscle activation prior to

297 contact, and in turn influence vertical peak force magnitude and impulse duration (Nigg, 1985).  
298 Muscle pre-activation characteristics may explain the differences in impact peak forces and times to  
299 impact peak between HI and LI groups. McNeal and colleagues (2007) showed that muscle  
300 activation timing and magnitude were related to take-off kinetics and kinematics in tumbling take-  
301 offs. In contrast with our hypothesis, the time to reach the impact peak was longer for the HI group.  
302 This may be due to the weaker push action of the LI group. The weaker push was observed from a  
303 qualitative analysis of the performance trials. It was noted that gymnasts of the LI group appeared  
304 to 'pull' or 'release' their hands from the table rather than push against it.

305 The LI group showed positive correlations between shoulder angles at hand contact and a  
306 braking impulse. Regarding technique, a statistical positive relationship between a shoulder angle  
307 and a braking and vertical impulse in the forward handspring on the floor has been identified as a  
308 performance factor influencing the 'blocking effect' (i.e. rapid push from the hands) at impact.  
309 Impact events with poor shoulder flexion have been associated with dissipation of ground reaction  
310 force (Nelso and Metzger, 1995).

311 Finally, the wrist and shoulder angles did not show significant differences between HI and  
312 LI groups. However, for HI impacts the relationships of the wrist with the shoulder angles, the  
313 times to impact peak forces and the loading rates demonstrated that gymnasts who approached the  
314 apparatus with the wrist more hyper-extended also had the shoulder more flexed, reached the  
315 impact peak slower and developed a lower loading rate. These results confirm that while the wrist  
316 angle at hand contact did not show any obvious direct relationship with hyperextension injury in  
317 relation to compressive load, the shoulder angle may be seen as a critical injury factor (Sands et al.,  
318 1993; Wadley and Albright, 1993; Whitin and Zernicke, 1998). It could be suggested that the  
319 shoulder angle at impact may play a role in determination of time to impact peak and thus of the  
320 magnitude of the loading rate.

321 Limitations in this study were primarily due to the exploratory-descriptive nature of the  
322 investigation. However, this is the first study to identify and characterize crucial kinetic and  
323 kinematic variables as potential injury contributors through direct measurement of the hand-table  
324 impact events on the gymnastics vaulting table. The findings obtained represent a valuable starting  
325 point to develop other investigations involving male gymnasts and more complex vault types.

326

## 327 **Conclusions**

328 High loading rates were found for both high and low intensity impact events. Results show  
329 that the short time to impact peak in conjunction with the position of the shoulder may be a likely  
330 contributor to injurious loading rates in addition to high impact peak forces.

331 Significant relationships between the loading rate and time to peak force were observed for  
332 high intensity loads. Peak force, time to peak force, and a shoulder angle at impact were identified  
333 as primary variables potentially involved in the determination of large repetitive loading rates on the  
334 forward handspring vault.

335

### 336 **Practical Implications**

337 Based on the findings of the present study it can be recommended to coaches that they  
338 encourage a rapid repulsive action and a shoulder position at full flexion in line with the torso. This  
339 study also suggests combining the practice of vaulting skills in combination with a specific  
340 flexibility and conditioning program in order to build stronger and more reactive upper extremity  
341 skill and strength. Finally, to completely understand the injury mechanisms during the vault  
342 exercise it will be necessary to investigate other intrinsic and extrinsic performance factors. For  
343 instance, further investigations of the elastic characteristics of the table surface are necessary to  
344 show if the vault table enhances the gymnast's ability to basically *take-off* (i.e. jump) from the  
345 hands.

346

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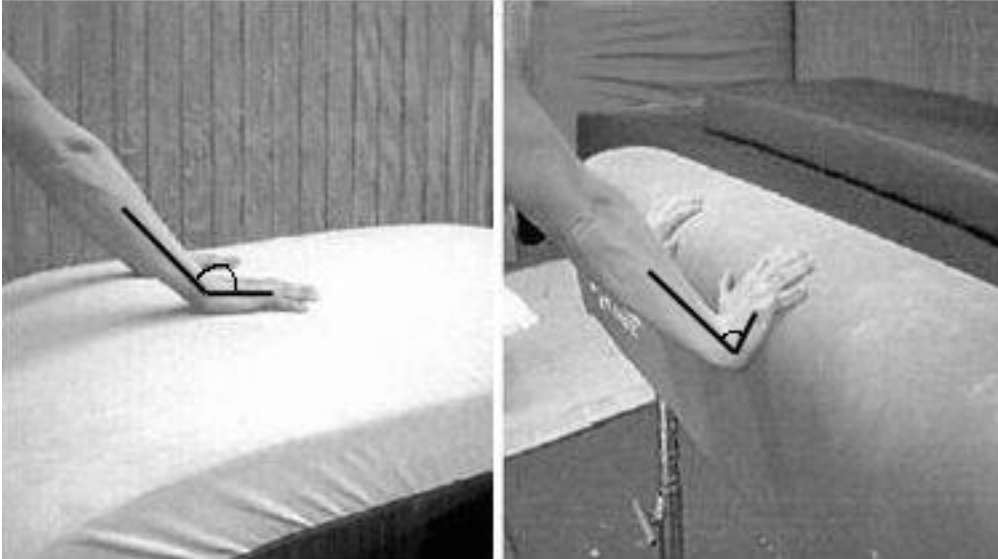
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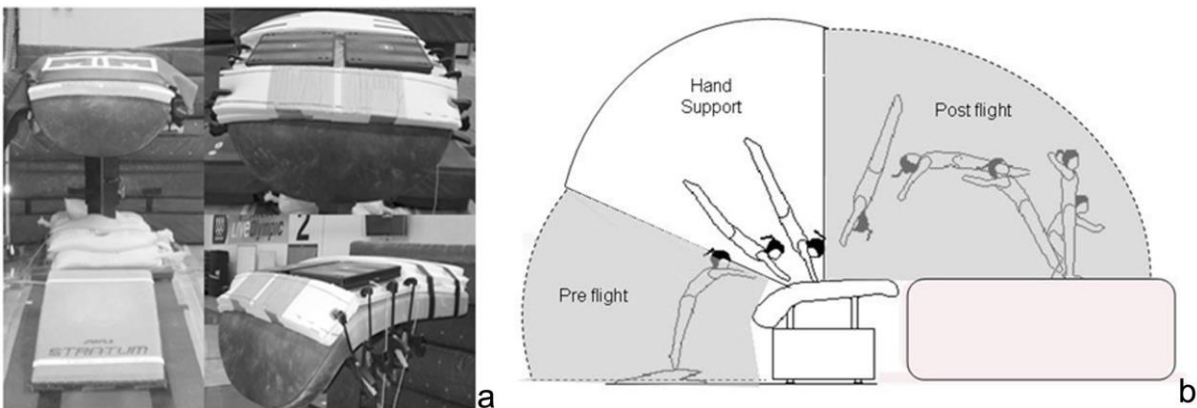
**Figure 1**



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*This picture is a demonstration of the hand placement. Vault table hand position for front handspring-type vaults on the horse vault (right) and table vault (left). Note that the wrist angle on the table vault surface appears less extended than on the horse vault (pictures modified with permission by Sands and McNeal, 2001).*

**Figure2**



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*2a-Two portable force platforms mounted on a plywood based, secured to the table and covered with a thin mat. The taped lines on the mat surface designed the edges of the force platforms to provide a visual target for the gymnasts` hands placement; (left).*

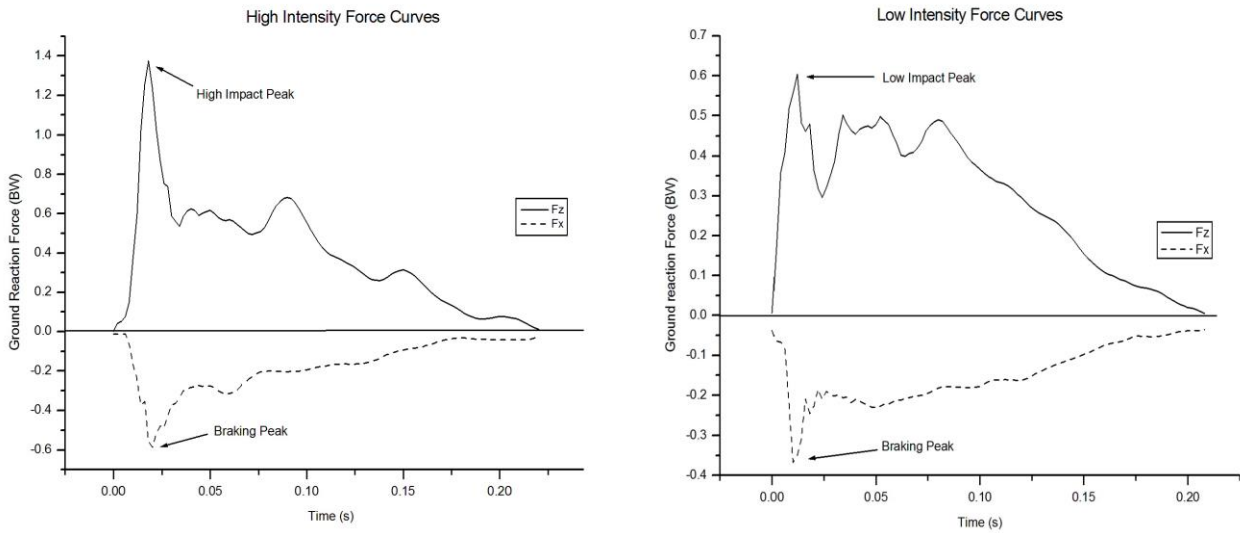
*2b - Forward handspring vault drill (right): Pre-flight (from springboard take-off to hand-table impact); Hand Support (from hand-table impact to hand-table take-off); Post-flight (from hand-*



456 *table take-off to feet-mat impact). Only the Hand support phase (white section in the picture) was*  
457 *analyzed in the present study.*

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**Figure 3.**



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*Sample, hand-support phase force-time data for the High (left) and Low (right) Load Intensity groups. The continuous and dashed lines represent the vertical ( $F_z$ ) and anterior-posterior ( $F_x$ ) forces, respectively.*