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# Index

# Editorial

Racket Sports have been widely studied in science for the last years. The purpose of this Journal is to aggregate the most important advances and researches to affect the development and directions of racket sports science from now on.

To reflect on the importance and impact a specialized journal can have in the field, we can put some perspective on its development:

- In 1993, the series of World Congresses in Science and Racket Sports took place, causing several publications to be released subsequently.
- Sharp (1998), recorded the duration of the rallies and the work-rest ratio in squash, using technology.
- The following years, the increase in computing power allowed to carry on studies with an unthinkable amount of data.

Thus, we know how investigation related to racket sports science has progressed in the past, and how crucial can the development of a specialised Journal be on the field.

The main purpose of this Journal is to generate new tools so we can look into the future from the paradigm of a specialised field, enhancing the research potential along with the participation of experts.

The ultimate goal is to create a platform for collaboration and cooperation among researchers, where sport scientist can come together and join forces to come up with new perspectives from where to keep expanding the knowledge involving all areas within the field of racket sports.

So we look into the future with high hopes of creating a place where knowledge, research and individuals can gather and share their experience, sparking new ideas and innovating in ways we have hardly dreamed of.

As Lees (2019), summarizes:

> *The beginnings of racket sport science, over 50 years ago, can be traced to the early pioneer researchers who, through their love of the game, gambled their future by edging away from their parent academic discipline towards a virgin field of discovery.*
>
> *They were able to make the transition and lay the foundations for others to follow. And follow they did. (…) Combined with the advancement of technology and the availability of computers, hundreds of individuals now had the possibility to develop their scientific skills, as the pioneers had done, through the love of their sport.*

And from their legacy, we keep developing the field.

David Cabello Manrique
Editor in Chief
International Journal of Racket Sports Science

# The benefits of the 5-week Table Stars @school program as part of physical education in primary schools – A pilot intervention study

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## Abstract

The Table Stars @school program was launched in 2010 to serve as a first introduction to table tennis in primary school children. The main aims of this pilot intervention study were 1. to evaluate the effect of Table Stars @school on the perceptuo-motor skills and selective attention in primary school children in comparison to regular physical education and 2. to find out how many and which children benefited more from Table Stars @school compared to regular physical education. A pilot intervention study was carried out including 177 children between 6 to 12 years from two regular primary schools. All children were tested by means of four perceptuo-motor tests (static balance, walking backwards, speed while dribbling, eye hand coordination) and a selective attention task (map mission). Both schools were exposed to both the Table Stars @school program and regular physical education in a different order. The results revealed no differences between the regular physical education classes and the Table Stars @school program on group level. However, both interventions showed different responders. Consequently, Table Stars @school seems to fit in as it meets the level of improvement of regular physical education classes and it can be of added value by addressing other children to improve perceptuo-motor skills and selective attention. Nevertheless, intensifying the program and/or integrating it into regular physical education is recommended to increase the effects and better add to the broader development of children.

Keywords: *Table Stars, Physical education and training, Child, Psychomotor performance, Racket sports*

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## Introduction

The Netherlands Table Tennis Association (NTTA) launched the so-called Table Stars @school program in 2010 (https://www.nttb.nl/speel-tafeltennis/jeugd/table-stars/ts-op-school; NTTB, 2018). This program is designed for children between 6-12 years as a first introduction to the sport of table tennis in primary schools. Table Stars @school can be used in physical education classes. It offers complete lessons which can be given by physical education teachers and/or table tennis trainers. The program has been developed in such a way that teachers/trainers can put together one or more lessons for each age group from a list of different exercises connecting to table tennis. Table Stars @school has been implemented in practice by the NTTA and it has been certified as an official intervention by the Dutch Ministry of Health, Welfare and Sport (https://menukaart.sportenbeweeginterventies.nl). Table Stars @school is a part of the full program 'Table Stars', which includes, besides the offer for schools, three other parts and possible moments of entrance: 'Table Stars @the club', 'Table Stars Challenge' and 'Table Stars the Battle'. Table Stars @the club is the sequel to Table Stars @school. In this part, children discover the table tennis club after the first introduction with the sport at school and continue to learn the first basic skills. The third part and entry point is Table Stars Challenge. The Table Stars Challenge offers table tennis clubs the opportunity to make children a good start with table tennis as a competitive sport. At this point, children are already members of the association and practice at their club. Children learn the rules and how to compete with other children. 'Table Stars the Battle' is an annual championship especially for primary school children. This championship is played in teams.

The aim of the NTTA by initiating Table Stars @school, a program outside and in addition the regular table tennis club trainings, was two-fold. First, the NTTA wanted to introduce as many children as possible to table tennis and let them explore and discover with Table Stars @school whether table tennis might be the sport that fits them. The recruitment of young members with Table Stars is an essential part of the NTTA's policy as it is vital for the NTTA's sustainability in future. More children can be reached by providing this program during the physical education classes in comparison with regular club trainings; at this moment, 250 school and 80 clubs use (parts) of Table Stars and more than 13,000 children are reached in the Netherlands every year (https://www.nttb.nl/nieuws/table-stars-wervend-product). Moreover, Table Stars @school is suggested to better connect children to table tennis than a regular table tennis training, because it includes exercises that are especially made for children between 6-12 years to learn table tennis fundamentals. Children are considered to experience fun and a sufficient level of success at these exercises.

Second, the NTTA wanted to provide a program that connects with the physical education curriculum and contributes to the development of young children. It is hypothesized that children benefit from this program regarding their perceptuo-motor skills by practicing the fundamental skills of table tennis (Balyi, 2001). The most prominent fundamentals of table tennis in Table Stars are considered (a combination of) static and dynamic balance skills (e.g. footwork), eye hand coordination (e.g. aiming, catching, juggling, hitting) and object control/manipulation (i.e. bat and ball control) (Faber et al., 2014; Table Tennis Canada, 2015). Although the regular physical education program in the Netherlands covers a part of these skills, not much attention is paid to the perceptuo-motor skills underlying most racket and batting sports that need a higher degree of coordination and (ball) control (Schmidt and Lee, 2011). In general, children practice the more gross perceptuo-motor skills like running, climbing, clambering and throwing and catching while using a relatively large ball (e.g. volleyball) during physical education classes in the Netherlands (http://tule.slo.nl). The more precise footwork (e.g. hopscotch, cross-steps and side-steps) and ball control skills while using an elongated arm and/or a smaller ball and the combination often receive less attention or are even neglected. Adding this to the physical education classes provides a wider range of skills that can be explored and practiced, which is considered to stimulate a broader skills development in children.

In addition to this, table tennis is acknowledged as a meticulous and cognitively-engaging sport (Best, 2010; Wang et al., 2016). Table Stars includes age-adequate, but relatively complex motor tasks that are closely connected to table tennis. The more complex skills or coordinative exercises are found to be more effective to improve concentration and attention tasks than simpler exercises (Budde et al., 2008). Moreover, nearly all forms of cognitive functioning involve attention (Best, 2010). Particularly selective attention, in which attention is directed to a specific relevant object (and not to the disruptive irrelevant ones), seems crucial in table tennis. Due to this specific characteristic of the sport, most exercises in table tennis practice are considered to require a relatively high level of attention. Also the exercises within Table Stars @school challenge the children's ability to focus on a certain task; only with a sufficient level of attention it is possible to fulfil the task successfully. Consequently, it is suggested that children might benefit from Table Stars @school also regarding their attention skills.

Although Table Stars @school has been implemented in practice by the NTTA and it has been certified as an official intervention, the contributing effect of Table Stars @school on children's development has not yet been studied. Since perceptuo-motor performance and cognitive functions are important in the overall development of children (Bushnell and Boudreau, 1993; Moffitt et al., 2011), this first pilot intervention study will cover this gap on the basis of the following research questions:

1. What is the effect of Table Stars @school in comparison to regular physical education on the perceptuo-motor skills and selective attention in primary school children (6-12 years)?
2. How many and which children benefit more from the Table Stars @school program compared to regular physical education?

## Materials and methods

### *Study design*

An intervention study was carried out in two regular public primary schools in the Netherlands within the period of October 2017 to February 2018. Both schools provide physical education classes of 45 min twice a week during regular school weeks. Figure 1 presents the design of the study. A baseline measurement (T0) has been conducted at both schools at the start of the study. Consecutively, the intervention Table Stars @ school was provided at school I, which lasted 5 weeks. The children of school II participated in their regular physical education classes in the same period. After this first period, the children of both schools were measured again (T1). After that, school II was provided with the Table Stars @school intervention for 5 weeks. The children of school I followed the regular physical education program in this period. A third measurement (T2) was conducted in both schools again after the intervention period of school II. This study and its informed consent procedure were approved by the ethical committee 'Commissie Mensgebonden Onderzoek' region Arnhem-Nijmegen (Nijmegen, The Netherlands; registration code 2017-3682) in full compliance with the Declaration of Helsinki. Written parental informed consent and children's consent were obtained prior to the first testing appointments at the primary school. All data were recorded in an anonymous data set. The authors declare no conflict of interest.

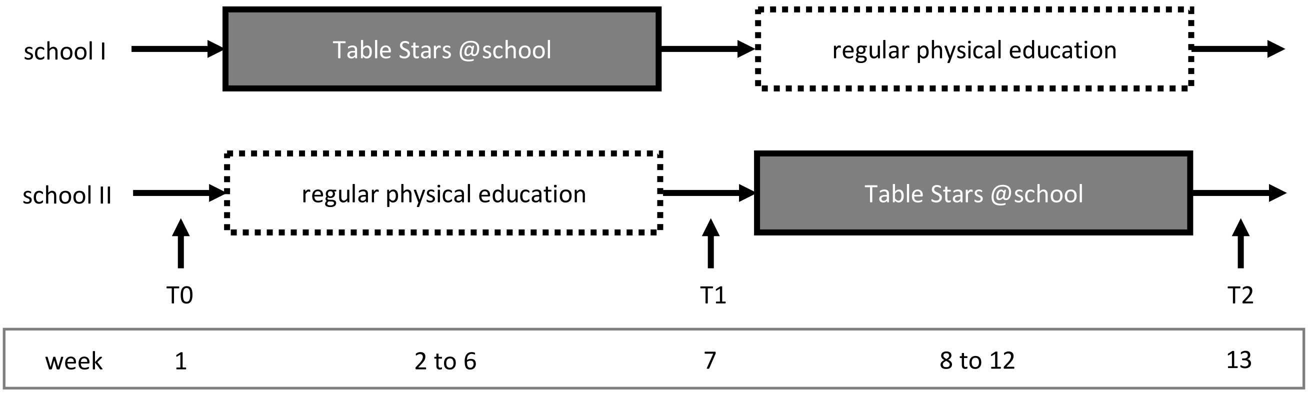


*Figure 1*. Study design

### *Participants*

Children between 6 to 12 years from class 3 to 8 were recruited at two regular public primary schools. Both schools educate without a certain religious or otherwise philosophical direction as the basis, include predominantly typically developing children and do not address specifically special target groups (e.g. children with behavior or learning disorders).

### *Interventions*

#### **Table Stars @school**

The intervention was carried out by two qualified NTTA trainers in both schools. They were familiar with Table Stars @school. The program lasted 5 weeks. In each week, one of the two physical education classes has been replaced by a Table Stars @school lesson. During the lessons, attention was paid to the following: aiming, footwork, balancing, effect, ball control and playing (returning the ball). Adjustments were made to the task per age group if necessary. For more information, see the detailed description in the 'Table Stars - the finest motor skills method' (NTTB, 2018).

#### **Regular physical education**

The regular physical education intervention was carried out by the classes' regular teachers from school. The lessons were based on the aims of the Dutch national expertise centrum of learning development. They used a mix of the learning themes: balancing, climbing, swinging, tumbling, running, aiming, juggling, goal games, tapping and romping. For more information: http://tule.slo.nl/Bewegingsonderwijs/F-KDBewegingsonderwijs.html). In each week, regular physical education lessons were provided twice.

### *Measurements*

The perceptuo-motor skills assessment of the children consisted of four test items: static balance (SB), walking backwards (WB), speed while dribbling (SD) and eye-hand coordination (EHC). SB and WB are selected to measure static and dynamic balance, respectively, while SD and EHC aim to measure the eye hand coordination and ball control (object manipulation). All perceptuo-motor items were selected from existing test batteries i.e. the Movement Assessment Battery for Children-2 (SB), the Körperkoordinationstest für Kinder-3 +EHC (WB and EHC) and the Dutch Motor Skills Assessment (SD) (Kiphard and Schilling, 2007; Faber et al., 2015; Henderson et al., 2007; Platvoet et al., 2018). Selective attention was measured with the map mission (MM) task, a test item of the Test of Everyday Attention for Children (Manly et al., 2001). The standardization of all test items is captured in protocols, which includes a detailed description of materials, set-up, assignment, demonstration, training phase, testing phase and registering test scores.

#### **Static balance (SB)**

The children were instructed to stand on one leg on a balance board. The maximum was set on 45 seconds. This modification to the original test item, which uses a maximum of 30 seconds, is made to maintain adequate responsiveness of the test items when used in the children of the relatively older ages (11-12 years). There were two attempts. Only the best time (s) was noted as final outcome (Henderson et al., 2007). The test-retest reliability of the original test item is considered good; intraclass correlation coefficient SB 0.99 ($p < 0,05$) (Wuang et al., 2012). As the nature of the test maintained, it is suggested that reliability is sufficient. Moreover, the original test item is able to discriminate between performance levels (Henderson et al., 2007).

**Walking backwards (WB)**

The children were instructed to walk backwards three times along of three balance beams (3 trials x 3 beams) with the same length (3 m) but differences in width (6 cm, 4.5 cm and 3 cm). The number of successful steps was scored as final raw outcome with a maximum of eight steps per trial, which comprises a maximum of 72 steps (8 steps x 3 trials x 3 beams) (Kiphard and Schilling, 2007). The test-retest reliability of the test items is considered good; intraclass correlation coefficient WB 0.80 ($p < 0,05$) (Kiphard and Schilling, 2007). Moreover, the test item is able to discriminate between performance levels (Platvoet et al., 2018; Vandorpe et al., 2011).

**Speed while dribbling (SD)**

'Speed while dribbling' used a zigzag circuit in which the players needed to move sideways as fast as possible while dribbling with a basketball using one hand. Players had one attempt in which time was measured in seconds (Faber et al., 2016). The test-retest reliability of the test items is considered good; SD 0.83 ($p < 0,05$) (Faber et al., 2015). Moreover, the test item is able to discriminate between performance levels (Faber et al., 2014; Faber et al., 2015; Faber et al., 2018).

**Eye hand coordination (EHC)**

During the eye-hand coordination test the children needed to throw a tennis ball on a flat wall at 1-meter distance with one hand and to catch the ball correctly with the other hand as many times as possible in 30 seconds. The best number of correct catches of two attempts was recorded as raw outcome score. The modification on the original protocol as proposed by Platvoet et al. (2018) was used for the children of the third and fourth classes (6-8 years); they were allowed to use both hands for catching. The test-retest reliability of the test items is considered good; intraclass correlation coefficient EHC 0.87 ($p < 0,05$) (Faber et al., 2015). Moreover, the test item is able to discriminate between performance levels (Faber et al., 2014; Faber et al., 2015; Faber et al., 2018; Platvoet et al., 2018).

**Map mission (MM)**

The children were given a printed A3 laminated city map with 80 targets (small restaurant symbols, 4 x 3 mm) randomly distributed across this map. Distracting symbols of a similar size (e.g. supermarket trolleys, cups, and cars) were also present. The children were instructed to find and circle as many target symbols as possible with a pen within one minute. The final score was the number of targets correctly marked (Manly et al., 2001). The test-retest reliability of the test items is considered good; intraclass correlation coefficient MM 0.88 ($p < 0,05$) (Manly et al., 2001). Moreover, the test item is able to discriminate between performance levels (Manly et al., 2001).

*Data collection*

Data were collected between October 2017 to February 2018. All children were tested under similar conditions. The perceptuo-motor tests were assessed in random order during two physical education classes. The test for selective attention was assessed during other regular classes. Total testing time for each child was approximately 10 minutes for the perceptuo-motor tests and 5 minutes for the selective attention task per testing moment. Test leaders were physical education students or table tennis trainers and instructed and trained to the same extent by an expert. All test leaders were blinded for the results of previous testing moments. In addition to the tests, the sex, the date of birth and the class of the children were recorded. From the birthday and class number, it was derived whether children rebounded or speeded up one class. Moreover, children were asked at the baseline measurement (T0) whether they participated in a ball sports (yes/no).

*Statistical analysis*

IBM SPSS Statistics 25 (IBM Corp., Armonk, New York, United States of America) was used for the statistical analyses. Sample characteristics were presented for the total group and the two schools separately. An independent t-test was used to test for difference in age between the two schools. Chi-square tests were conducted to examine differences in group characteristics between the two school regarding sex and sport participation (ball sport yes/no). Children with injuries/illness that were not able to attend one or more tests were excluded from further analyses in which these results were needed.

Then first, the baseline outcomes were analyzed to test for significant differences between schools by means of an independent t-test. Second, the effect of the interventions on group level were analyzed in three different ways to make a clean evaluation: 1.) a comparison for both schools separately using a paired t-test 2.) a comparison including both schools using a paired t-test and 3.) a comparison taking only into account the first period (T0-T1) using an independent t-test. The main reasons for this multiple approach was the absence of a clear wash-out effect as a consequence of the nature of the interventions and design (Wellek and Blettner, 2012); this study cannot be perceived as a clean crossover design. Finally, it was analyzed how many and which children benefit most from Table Stars @school and the regular physical education lessons. For this purpose, we identified the so-called 'responders' and 'non-responders' for balance, eye-hand coordination/ball control and selective attention for both interventions. A responder on balance showed a better development of performances on both SB and WB after either regular physical education or Table Stars @school. A responder on eye-hand coordination/ball control showed a better development on both SD and EHC after either regular physical education or Table Stars @school. A responder on selective attention scored more than 9 points (i.e. smallest detectable change of MM) better after either regular physical education or Table Stars @school. Non-responders did not meet these criteria. Difference between the non-responders, the regular physical education responders and the Table Stars @school responders were evaluated with a Chi-square tests for sex and ball sport participation and an ANOVA for age and the test outcomes at baseline (T0). Cohen's rules of thumb are used on the magnitudes of the effect sizes (Cohen, 1988). Alpha was set at 0.05 for significance for all analyses.

## Results

*Sample characteristics*

All children from class 3 to 8 (n=179) and their parents/care-takers were approached to participate in this study. For two children, one of each school, no informed consent was signed. The sample characteristics are presented in Table 1. No significant differences were found between the schools regarding age and the distribution of sex and sports participation (ball sport yes/no) ($p > 0.05$).

Table 1.
*Sample characteristics*

| | Total | School I | School II | *p*-value | Cohen's *d* | Cramer's V |
|---|---|---|---|---|---|---|
| Number | 177#(100%) | 102#(100%) | 75#(100%) | | | |
| Age (years) | 8.8 (1.6) | 8.6 (1.6) | 9.0 (1.6) | 0.515 | 0.251 | |
| Sex | | | | 0.807 | | 0.018 |
| - boys | 101 (57%) | 59 (58%) | 42 (56%) | | | |
| - girls | 76 (43%) | 43 (42%) | 33 (44%) | | | |
| Ball sport | | | | 0.793 | | 0.020 |
| - no | 90 (51%) | 51 (50%) | 39 (52%) | | | |
| - yes | 87 (49%) | 51 (50%) | 36 (48%) | | | |
| Speeded up | 1 (0.5%) | 1 (1%) | 0 (0%) | | | |
| Rebounded | 54 (31%) | 31 (30%) | 23 (31%) | | | |

Data are frequencies (valid percent), except for age which is presented in mean (SD).
#missing n=2 (1 per school, no informed consent was signed)

*Baseline comparison*

Table 2 present the comparison of the two schools on the baseline measurement concerning the test outcomes. The mean scores are presented per test item. The independent t-tests show that there existed a significant difference with a small effect size between two school at the baseline measurement for WB; the children from school II outperformed the children of school I at WB (p = 0.040; Cohen's d = 0.318).

Table 2.
*Baseline comparison*

| | School I | | School II | | | |
|---|---|---|---|---|---|---|
| | n | mean (SD) | n | mean (SD) | *p*-value | Cohen's *d* |
| SB (s) | 102 | 18.2 (15.3) | 72 | 19.3 (14.5) | 0.611 | 0.073 |
| WB (steps) | 100 | 33.7 (15.8) | 72 | 41.2 (14.9) | 0.002* | 0.488 |
| SD (s) | 100 | 26.7 (10.3) | 73 | 27.9 (8.9) | 0.404 | 0.124 |
| EHC (catches) | 100 | 11.3 (8.0) | 71 | 10.5 (6.1) | 0.461 | 0.112 |
| MM (targets) | 101 | 34.5 (11) | 74 | 37.0 (12.4) | 0.155 | 0.213 |

SB = static balance, WB = Walking backwards, SD = speed while dribbling, EHC = eye hand coordination, MM = map mission.
Independent t-test are used to test for differences between groups. *$p < 0.05$.

*Intervention effect – group analyses*

The comparison between Table Stars @school and regular physical education are presented in Table 3. Part a. and b. show the effect in paired analyses for both schools, separately. Part c. includes both schools in a paired comparison, where the order of the interventions in both schools is different (Fig. 1). Part d. compares school I (i.e. Table Stars @school) and school II (i.e. regular physical education) only for the difference between T0-T1. The separate analysis for school I shows a significant improvement with small and medium effect sizes in favor of the Table Stars @school intervention regarding static balance (p = 0.004; Cohen's d = 0.300) and selective attention (p < 0.001; Cohen's d = 0.701), respectively. In contrast, the separate analysis for school II shows a significant improvement with small and medium effect sizes in favor of the regular physical education intervention regarding selective attention (p < 0.001; Cohen's d = 0.450) and walking backwards (p < 0.001; Cohen's d = 0.501), respectively. In the intervention comparison including both schools in a paired analysis (Table 3, part c.), only one significant effect remains in favor of the Table Stars @school intervention (p = 0.038). It must be acknowledged that this is a significant effect with only a small effect size (Cohen's d = 0.172). When taking into account the first period (T0-T1) of the study, only on the eye hand coordination test there is a significant difference with a small effect size between the intervention in favor of the regular physical education (p = 0.005; Cohen's d = 0.447).

Table 3.
*Intervention comparison*

a. Intervention comparison for school I

| | n | regular physical education mean difference T2-T1 (SD) | Table Stars @school mean difference T1-T0 (SD) | *p*-value | Cohen's *d* |
|---|---|---|---|---|---|
| SB (s) | 95 | 1.29 (13.62) | 7.93 (13.6) | 0.004* | 0.300 |
| WB (steps) | 85 | 3.12 (8.04) | 5.01 (9.7) | 0.224 | 0.127 |
| SD (s) | 94 | -0.21 (5.34) | -0.08 (6.46) | 0.904 | 0.012 |
| EHC (catches) | 86 | 1.29 (4.13) | 0.01 (4.02) | 0.091 | 0.185 |
| MM (targets) | 82 | 2.57 (6.08) | 9.38 (5.71) | <0.001* | 0.701 |

b. Intervention comparison for school II

| | N | regular physical education mean difference T1-T0 (SD) | Table Stars @school mean difference T2-T1 (SD) | *p*-value | Cohen's *d* |
|---|---|---|---|---|---|
| SB (s) | 55 | 7.76 (13.46) | 2.91 (14.70) | 0.148 | 0.198 |
| WB (steps) | 58 | 5.03 (9.04) | -2.36 (9.96) | <0.001* | 0.501 |
| SD (s) | 57 | -2.01 (5.57) | -1.92 (4.87) | 0.938 | 0.010 |
| EHC (catches) | 59 | 1.97 (3.99) | 1.71 (4.46) | 0.781 | 0.036 |
| MM (targets) | 66 | 8.15 (6.36) | 3.94 (4.82) | <0.001* | 0.450 |

c. Intervention comparison for both schools

| | n | regular physical education mean difference (SD) | Table Stars @school mean difference (SD) | *p*-value | Cohen's *d* |
|---|---|---|---|---|---|
| SB (s) | 150 | 3.66 (13.75) | 6.09 (14.18) | 0.209 | 0.103 |
| WB (steps) | 143 | 3.89 (8.48) | 2.02 (10.43) | 0.150 | 0.121 |
| SD (s) | 151 | -0.89 (5.48) | -0.78 (5.96) | 0.886 | 0.012 |
| EHC (catches) | 145 | 1.57 (4.07) | 0.70 (4.27) | 0.137 | 0.124 |
| MM (targets) | 148 | 5.06 (6.78) | 6.95 (5.97) | 0.038* | 0.172 |

| d. Intervention comparison T0-T1 | | | | | | |
|---|---|---|---|---|---|---|
| | n | School II<br>regular physical education<br>mean difference (SD) | n | School I<br>Table Stars @school<br>mean difference (SD) | *p*-value | Cohen's *d* |
| SB (s) | 65 | 7.10 (14.20) | 98 | 8.03 (13.61) | 0.675 | 0.067 |
| WB (steps) | 71 | 5.03 (9.54) | 95 | 5.59 (9.64) | 0.710 | 0.058 |
| SD (s) | 65 | -1.84 (5.70) | 97 | -0.13 (6.38) | 0.084 | 0.283 |
| EHC (catches) | 72 | 1.94 (3.93) | 95 | 0.18 (3.95) | 0.005* | 0.447 |
| MM (targets) | 73 | 7.66 (6.29) | 98 | 9.03 (5.80) | 0.142 | 0.226 |

SB = static balance, WB = Walking backwards, SD = speed while dribbling, EHC = eye hand coordination, MM = map mission. For a, b, and c paired t-test were used to test for differences. For d, an independent t-test was used to test for differences. $^*p < 0.05$.

## *Response analyses*

Table 4 presents the number of children that could be identified as non-responder or responder for balance, eye-hand coordination/ball control and selective attention. Regarding the perceptuo-motor skills it seemed that approximately 25% of the children responded on the regular physical education lessons versus 20% on the Table Stars @school lessons. In contrast, for the selective attention approximately 25% of the children were identified as responders of the Table Stars @school program versus only 13% of the regular physical education program. No significant differences were found between the non-responders and responders regarding their age, sex, ball sport participation and the baseline test outcomes, except for one. Table Stars @school responders scored significantly lower with small effect sizes on the balance tests (SB: p = 0.020, partial η2 = 0.501; WB: p = 0.011, partial η2 = 0.501).

Table 4.
*Response analysis*

| | Non-responders<br>Mean (SD) | Regular physical education<br>Mean (SD) | Table Stars @school<br>Mean (SD) | F-value/ $x^2$ | p-value | partial $\eta^2$/ Cramer's V |
|---|---|---|---|---|---|---|
| a. Responder on balance[1] | | | | | | |
| | n= 66 | n = 33 | n = 25 | | | |
| Age (years) | 8.7 (1.6) | 9.0 (1.8) | 8.7 (1.7) | 0.395 | 0.675 | 0.006 |
| Sex (boy:girls) | 36:30 | 14:11 | 18:16 | 0.056 | 0.973 | 0.021 |
| Ball sport (no:yes) | 33:33 | 11:14 | 19:15 | 0.823 | 0.663 | 0.081 |
| Test-outcomes at T0 | | | | | | |
| SB (s) | 21.1 (15.8) | 19.9 (14.5) | 11.6 (10.2) | 4.023 | 0.020* | 0.062 |
| WB (steps) | 39.2 (15.6) | 37.6 (15.9) | 28.4 (12.5) | 4.658 | 0.011* | 0.071 |
| SD (s) | 28.4 (10.9) | 26.4 (9.1) | 27.6 (11.6) | 0.395 | 0.674 | 0.006 |
| EHC (catches) | 11.0 (7.8) | 10.8 (6.5) | 11.5 (7.9) | 0.069 | 0.933 | 0.001 |
| MM (targets) | 34.3 (12.4) | 34.2 (12.4) | 35.6 (10.2) | 0.744 | 0.477 | 0.012 |

| b. Responder on eye-hand coordination/ball control[2] | | | | | | |
|---|---|---|---|---|---|---|
| | n= 69 | n = 31 | n = 25 | | | |
| Age (years) | 8.9 (1.6) | 8.5 (1.7) | 8.8 (1.7) | 0.469 | 0.627 | 0.008 |
| Sex (boy:girls) | 38:32 | 14:11 | 15:16 | 0.400 | 0.819 | 0.056 |
| Ball sport (no:yes) | 41:29 | 11:14 | 13:18 | 3.100 | 0.212 | 0.157 |
| Test-outcomes at T0 | | | | | | |
| SB (s) | 18.1 (14.2) | 19.3 (17.0) | 21.5 (14.9) | 0.469 | 0.627 | 0.008 |
| WB (steps) | 36.5 (14.6) | 36.03 (18.3) | 40.6 (15.8) | 0.735 | 0.481 | 0.012 |
| SD (s) | 28.3 (11.0) | 28.1 (10.2) | 25.8 (9.5) | 0.553 | 0.577 | 0.009 |
| EHC (catches) | 10.3 (7.4) | 12.4 (8.5) | 11.8 (5.7) | 0.992 | 0.374 | 0.016 |
| MM (targets) | 34.6 (11.4) | 34.6 (12.3) | 36.9 (11.9) | 0.454 | 0.636 | 0.007 |
| c. Responder on selective attention[3] | | | | | | |
| | n= 91 | n = 19 | n = 36 | | | |
| Age (years) | 8.6 (1.7) | 9.0 (1.6) | 8.83 (1.5) | 0.458 | 0.634 | 0.006 |
| Sex (boy:girls) | 52:40 | 19:17 | 11:9 | 0.148 | 0.929 | 0.032 |
| Ball sport (no:yes) | 43:49 | 21:15 | 12:8 | 2.085 | 0.353 | 0.119 |
| Test-outcomes at T0 | | | | | | |
| SB (s) | 17.4 (14.1) | 23.7 (14.4) | 22.3 (16.9) | 2.256 | 0.109 | 0.031 |
| WB (steps) | 37.7 (15.4) | 40.1 (14.2) | 37.6 (18.9) | 0.191 | 0.827 | 0.002 |
| SD (s) | 27.3 (9.4) | 30.1 (10.1) | 26.9 (11.2) | 0.755 | 0.472 | 0.011 |
| EHC (catches) | 10.6 (6.5) | 8.5 (8.4) | 12.2 (8.1) | 1.696 | 0.187 | 0.023 |
| MM (targets) | 35.2 (11.6) | 35.6 (12.0) | 34.0 (13.1) | 0.115 | 0.891 | 0.002 |

SB = static balance, WB = Walking backwards, SD = speed while dribbling, EHC = eye hand coordination, MM = map mission.

Differences between responders and non-responders were tested by means of an ANOVA (age, SB, SB, SD, EHC and MM) or Chi-square test (sex and ball sport). [1]A responder on balance showed a better development of performances on both SB and WB after either regular physical education or Table Stars @school. [2]A responder on eye-hand coordination/ball control showed a better development on both SD and EHC after either regular physical education or Table Stars @school. [3]A responder on selective attention scored more than 9 points (i.e. smallest detectable change of MM) better after either regular physical education or Table Stars @school. $^{*}p < 0.05$.

## Discussion

The results of this first pilot intervention study indicate that the 5-week Table Stars @school program contributes at a similar level to the development of children in primary schools as regular physical education. For that reason, there seems to be no opposing arguments for its use. Moreover, it appeared that 20-25% of the children improved more during the Table Stars @school intervention when compared to the regular physical education. As no differences could be found between the responders of the Table Stars @school program and the regular physical education in the age, sex, ball sports participation and the test results at baseline, this might be due to other reasons. Perhaps difference in motivation within children for both interventions can explain this (Lewthwaite and Wulf, 2017). As such, Table Stars @school might be of added value to the regular physical education as its exercises may attract and stimulate other children to improve their skills.

Nevertheless, it is important to critically evaluate the set-up and results of this study. A first important issue is the total practice time during the Table Stars @school. As the proposed intervention is only 5-weeks with a frequency of one lesson a week, it is quite difficult to reach a significant and practically different skills level. It is likely that more time on the task is needed to reveal a contribution of the specific Table Stars @school exercises to the enhancement of perceptuo-motor skills and selective attention. The results now show that the 5-week program of Table Stars @school yields similar results as the regular physical education class. However, it was hypothesized that it would contribute to a higher extent to the development than the regular offer. Is it likely that intensifying the program and use at least both physical education classes for 5-weeks for the Table Stars @school program is crucial to obtain improvement (Platvoet et al., 2016). This would not only enlarge the amount of practice, but will also be a fairer comparison to regular physical education. Additionally, one might want to consider integrating exercises of Table Stars @school program in the physical education program to really make a difference. This would enrich the current program and get rid of the 'drop in the ocean effect', thus letting children improve a wider range of skills on a long-term base that is of added value for a broader development. It is not only about promoting a sport, but contributing to the children's development through (the fundamentals of) sports.

Another issue is the influence of children's other activities (e.g. sports history and (deliberate) play). Although we checked for the children's current participation in ball sports, we did not take into account their full sports history including the quality and quantity of previous and current training (Hopwood et al., 2016). Moreover, it is difficult to estimate a child's participation in other activities like (deliberate) play in- and outside. However, this information could provide a better insight when profiling the responders and non-responders. In addition to this, it is recommended to consider the criteria for the identification of the responders and non-responders in future research. Although, it was attempted to be as transparent and valid as possible, other solutions might fit as well. Yet, careful selection of the criteria and analyses are required to not over- or underestimate the effect of a certain intervention (Wellek and Blettner, 2012).

Finally, it must be acknowledged that the group size was different in both schools. As it was not practicable to conduct a randomized control trial with a stratification per school, both interventions were provided per school in a different order (Fig. 1). This caused a difference in the subsamples for one specific intervention order, which might have affected the results of the intervention analyses; there were more children in school I which caused relatively more weight for that school in the analysis including both schools. Therefore this study's results should be interpreted with caution. Additionally, it must be mentioned that complete-case approach was followed in this analysis of this study. Although, there is no suspicion of a systematic drop-out, the missing values raised up to approximately 30% of the total sample which might have biased the study results to some extent (Eekhout et al., 2012). It is recommended in future studies to avoid missing values or use imputation techniques to better deal with missing data.

## Conclusions

To summarize, the Table Stars @school program was evaluated in comparison to regular physical education lessons concerning the development of perceptuo-motor skills and selective attention. Generally speaking it seems that the Table Stars @school intervention yields similar effects as regular physical education, however, it might attract other children to develop their skills. For that reason, it seems legitimate to implement Table Stars @school in the original form in physical education classes. Yet, it is recommended for future to intensify the 5-week program or integrate it into the physical education classes to increase the effects and contribute to a broader development. This is expected to contribute to the children's development regarding their perceptuo-motor and attention skills to a higher extent.

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# Physiological, neuromuscular and perceived exertion responses in badminton games

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## Abstract

The purpose of this study was to characterise the physiological, neuromuscular and perceived exertion variables during a badminton match and to assess the influence of these variables on the characteristics of the game. Each variable was measured before, every ten minutes, and ten and twenty minutes after a badminton game. Using a lactate device, a heart rate monitor, an accelerometric system, a dynamometer, a camera and a Borg scale, twelve games between elite players were analysed. An increase was found in the heart rate, blood lactate and in the recovery time, while a decrease was found in the power output of the lower and upper limb joints and shot frequency. These results suggest the capability of the players to preserve a high intensity of performance for as long as possible despite general fatigue. The fatigue induced by changes in physiological variables is affected more by the intensity of the stroke rather than the duration of the rallies. The perceived exertion is thought to be a combination of attentional and neuromuscular fatigue rather than related to changes in metabolites. Consequently, in future studies, researchers and trainers should consider the fatigue state as a means to increase players' ability.

Keywords: *Performance, Fatigue, Skill, Biomechanics, Mental fatigue*

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## Introduction

Badminton is an extremely demanding sport that requires changes of direction (Heller, 2010), generates high power for explosive shots, rapid movements (Phomsoupha & Laffaye, 2015) and extended matches (Lees, 2003). Competitive matches last between 40 min (Cabello, Padial, Lees & Rivas, 2004) and one hour (Phomsoupha & Laffaye, 2015), with approximately 80% of rallies lasting less than 10 s (Faude et al., 2007).

Several studies have reported on the temporal structure of a match by measuring variables such rally duration (RD, time elapsed from the serve until the shuttle hit the ground or the net), recovery time (RT, time elapsed from the shuttle hit the ground or the net until the racket hit the shuttle for the following serve), effective playing time (EPT, the sum of the rally times divided by the match duration multiplied by a hundred) and shot frequency (SF, the number of shots divided by the effective playing time). A recent review of literature (Phomsoupha & Laffaye, 2015) refer to a typical badminton match as having 7.7 s of RD, 15.4 s of RT, 32.1% of EPT and 1.02 $s^{-1}$ of SF. Furthermore, the total duration and shot frequency of a badminton game considerably increased since the Olympic Games of 1992, suggesting an increase of the intensity of the game (Laffaye, Phomsoupha, & Dor, 2015).

From a physiological point of view, badminton is an intermittent activity with high-intensity short rallies with RT twice the length of the RD, requiring energy from both the aerobic (60-70%) and the anaerobic (30 %) systems. Further, male players' average maximal heart rate is 191.0 beats/min, which is over 90% of their maximal heart rate (%$HR_{max}$) with the maximum blood lactate concentration being around 7.0 mmol/L (Phomsoupha & Laffaye, 2015).

To sustain such an intensity and produce powerful shots, players have to produce a high level of force from upper-limb joints in order to hold the racket and to stroke the shuttlecock at high velocity, and from lower-limb joints to move quickly, to lunge and to jump. Only one study has reported the hand-grip strength of skilled badminton players and this was found to be between 450 and 500 N (Abián-Vicén, Del Coso, González-Millán, Salinero, & Abián, 2012). This is close to the values found in tennis where the racket is also held strongly (Ohguni, Aoki, Sato, Imada, & Funane, 2009). Lower-limb power production reveals a mean value about 32 W/kg for national players during a counter-movement jump (Abián-Vicén et al., 2012). Moreover, several actions, like jumping, changing of direction or split stepping necessitate a pre-stretch of the extensor muscles of the lower-limb. For instance, the split step corresponds to a small bounce synchronized with the opponent's stroke and initiates the movement. This action requires the efficiency of the stretch-shortening cycle (SSC), which could be assessed by measuring the leg stiffness (LS). This variable has been fully highlighted in tennis (Maquirriain, 2013), with values ranged between 20 $kN.m^{-1}$ to 35 $kN.m^{-1}$, but has never been recorded during a badminton match, despite a comparable neuromuscular constraints of the lower-limb.

These data reveal the high intensity of game, but up to now, few studies have investigated the fatigue state of badminton players during a game. Only one study has compared several physiological and biomechanical variables before and after the match (Abián-Vicén et al., 2012), but only as secondary variables in order to understand the process of dehydration. The psychological cost of fatigue is generally assessed with the ratings of perceived exertion (RPE) (Borg, Ljunggren, & Ceci, 1985) allowing a global view on central fatigue (that related to the stress on the participants' heart and lungs) and peripheral fatigue (that related to the stress on the limbs and joints). To obtain an accurate assessment of exertion, it seems necessary to process a continued recording of physiological, neuromuscular and psychological variables during a match.

Based on this theoretical background, the aim of this paper is: (a) to examine changes in game characteristics, physiological, neuromuscular, and perceived exertion variables during a prolonged badminton game; and (b) to assess the link between these variables and variables derived from a notational and temporal analysis.

## Material and Methods

### *Participants*

Twelve male elite single players (age: 25.34 ± 3.22 years; height: 179.43 ± 4.21 cm; body mass: 79.76 ± 12.48 kg; body fat: 17.12 ± 6.33%; muscle composition: 42.72 ± 2.18%; training practice: 7.18 ± 3.23 hours/week) with international and national experience participated in this study. They were fully informed about the protocol before participating in this study and they signed an informed consent form. Ethical approval was granted by the university Human Ethics Committee and followed principles of the Declaration of Helsinki.

### *Design & Procedures*

The match was a one-hour simulated badminton match. Players were permitted an interval of no more than 10 s between each rally during the game. The experimentation was conducted with brief breaks to collect and record blood samples, jumps and RPE every 10 min, and at 10 and 20 min after (Figure 1). A camera was also placed at back of the court to record the entire match as described by Laffaye et al. (2015). One week before, a shuttle run test (Leger & Lambert, 1982) was conducted to determine maximum oxygen uptake (57.44 ± 5.35 mL/kg/min) and maximum heart rate (187.76 ± 5.14 beats/min).

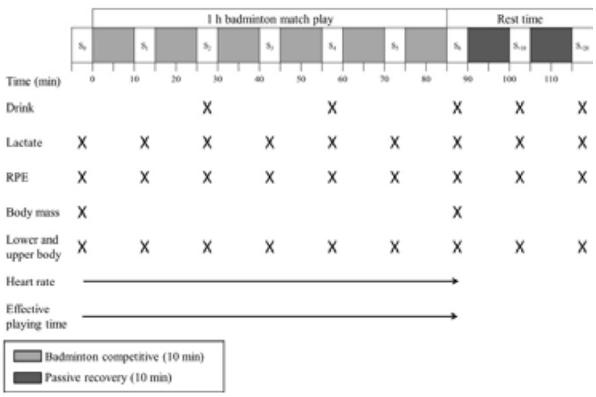

Figure 1. Experimental Set-up.

*Game characteristic variables.* The temporal pattern of the game was recorded with a video camera (HDR-XR260VE; Japan). Based on this recording, an investigator collected: (a) RD ; (b) RT; (c) EPT; and, (d) SF. The notational structure of each rally was performed on: (e) type of stroke (clear, drop, smash, net and, lob); (f) type of service (short and long); and, (g) way the point was won (direct point, forced error and, unforced error).

*Physiological variables.* To establish blood lactate (BLa) concentration, blood was collected from the fingertip of the arm not holding the racket, using a Lactate Pro portable device (Arkray®, Japan). Heart rate (HR) was registered using short range radio telemetry (RS400; Finland).

*Vertical jumps.* All vertical jumps were recorded using an accelerometric system at a frequency of 500 Hz (Myotest©, Switzerland), in three ways: (a) squat jump (SJ); (b) countermovement jump (CMJ); (c) with rebounds during a hopping-in-place jumping test with five repeated jumps maximizing jump height and reducing ground contact time for optimizing leg stiffness (LS). During each jump, the participants maintained their hands on their hips and perform two jumps. The performance was calculated from flight time by the device (Choukou, Laffaye, & Taiar, 2014). Vertical force and power were assessed from vertical velocity, by calculating the integration of data (Cavagna, 1975). LS was calculated by the formula of Dalleau, Belli, Viale, Lacour, & Bourdin (2004).

*Hand-Grip (HG) and Finger-Grip Force (FG).* The procedure for obtaining maximum HG and FG strength was that recommended by the American Society of Hand Therapists. Subjects were instructed to sit straight back, with the racket arm elbow angle at 90° and the forearm in a neutral position, then apply maximum isometric effort for 3 s to the dynamometer (Camry EH-101©, US).

*Psychological variables.* Each participant was requested to reveal CPE and PPE according to the 6-20 Borg scale every 10 min (Borg et al., 1985). CPE was related to the stress on the participants' heart and lungs while PPE concerned the stress on the limbs and joints.

### *Statistical Analysis*

The statistical design was a repeated measure analysis of variance on the recorded variables. Statistical significance was accepted at $p < 0.05$ and was followed by up with post-hoc comparisons between each session using Bonferroni adjustments as appropriate and power (β). Eta squared ($\eta^p$) were used to determine the effect sizes. Lastly, Spearman's correlation coefficients were calculated to determine the relationships between selected variables (Statistica 10 software, StatSoft Inc., Tulsa, US).

## Results

Mean RD, RT and, EPT were 5.81 ± 0.32 s, 8.04 ± 0.35 s and 41.54 ± 1.43%, respectively. No effect was found on the game characteristics of RD ($F_{5,\ 1220}$ = 0.893, $P$ = 0.485; $\eta^p$ = 0.029) nor EPT ($F_{5,\ 25}$ = 2.247, $P$ = 0.059; $\eta^p$ = 0.016), whereas RT increased by +9% ($F_{5,\ 1220}$ = 0.0372, $P$ = 0.864; $\eta^p$ = 0.058) and SF decreased with service (-7%, $F_{5,\ 1220}$ = 7.473, $P$ < 0.001; $\eta^p$ = 0.153) and without service (-9%, $F_{5,\ 1220}$ = 3.701, $P$ = 0.012). A strong correlation was found between RD and RT ($r$ = 0.742; $P$ < 0.001), a moderate correlation between SF and RD ($r$ = 0.504; $P$ < 0.001) and a strong and negative correlation between RT and SF ($r$ = -0.881; $P$ < 0.001). The distributions of each stroke were insignificant (Table 1). There was a strong correlation between SF and HR ($r$ = 0.884; $P$ < 0.001).

Table 1.

*Temporal and notational variables during each test session at $S_1$: 10th min; $S_2$: 20th min; $S_3$: 30th min; $S_4$: 40th min; $S_5$: 50th min and $S_6$: 60th min of badminton playing exercises.*

| Measure | $S_1$ $M \pm SD$ | $S_2$ $M \pm SD$ | $S_3$ $M \pm SD$ | $S_4$ $M \pm SD$ | $S_5$ $M \pm SD$ | $S_6$ $M \pm SD$ | $P$ | β | $\eta^p$ |
|---|---|---|---|---|---|---|---|---|---|
| Duration of rallies (s) | 5.80 ± 0.25 | 6.28 ± 0.36 | 5.98 ± 0.28 | 5.91 ± 0.38 | 5.56 ± 0.26 | 5.53 ± 0.27 | 0.484 | 0.323 | 0.171 |
| Recovery time (s) | 7.68 ± 0.24 $^{5;6}$ | 7.82 ± 0.26 $^{5;6}$ | 7.81 ± 0.22 $^{5;6}$ | 8.03 ± 0.26 | 8.31 ± 0.17 $^{1;2;3}$ | 8.43 ± 0.37 $^{1;2;3}$ | 0.003 | 0.942 | 0.487 |
| Effective playing time (s) | 251.83 ± 6.18 | 258.83 ± 7.42 | 253.34 ± 7.76 | 251.66 ± 7.72 | 236.51 ± 5.91 | 241.53 ± 6.58 | 0.059 | 0.676 | 0.331 |
| Stroke frequency with service ($s^{-1}$) | 1.06 ± 0.04 $^{3;4;5;6}$ | 1.03 ± 0.05 $^{5;6}$ | 1.02 ± 0.06 $^{1;5;6}$ | 1.01 ± 0.04 $^{1}$ | 0.99 ± 0.04 $^{1;2;3}$ | 0.97 ± 0.02 $^{1;2;3;4}$ | < 0.001 | 0.999 | 0.651 |
| Stroke frequency without service ($s^{-1}$) | 1.03 ± 0.02 $^{5;6}$ | 1.01 ± 0.05 $^{5;6}$ | 1.01 ± 0.08 $^{5;6}$ | 1.00 ± 0.07 $^{6}$ | 0.97 ± 0.08 $^{1;2;3}$ | 0.96 ± 0.08 $^{1;2;3;4}$ | 0.012 | 0.863 | 0.425 |
| Clear (%) | 16.43 ± 0.21 | 17.72 ± 0.96 | 16.32 ± 0.65 | 18.02 ± 0.81 | 17.74 ± 1.26 | 16.63 ± 0.51 | 0.857 | 0.0732 | 0.134 |
| Drop (%) | 15.34 ± 0.61 | 16.91 ± 1.43 | 15.96 ± 2.47 | 16.81 ± 2.32 | 16.77 ± 1.68 | 16.10 ± 1.83 | 0.794 | 0.0471 | 0.152 |
| Smash (%) | 15.95 ± 0.46 | 14.20 ± 0.81 | 14.02 ± 0.74 | 14.81 ± 0.71 | 14.49 ± 0.64 | 17.14 ± 0.67 | 0.654 | 0.263 | 0.518 |
| Net (%) | 27.63 ± 0.23 | 26.54 ± 1.08 | 29.51 ± 0.93 | 27.94 ± 1.16 | 27.71 ± 1.13 | 28.59 ± 0.84 | 0.728 | 0.102 | 0.175 |

Values are mean and standard deviation. Significant difference at the post hoc test with n.

During the match, the mean HR was 168.3 ± 13.2 beats/min, corresponding to 85%$HR_{max}$. Blood lactate increased from an initial value of 1.62 ± 0.43 mmol/l to 6.87 ± 6.33 after 10 min of play ($F_{8, 88}$ = 3.904, $P$ < 0.001; $\eta^p$ = 0.262), showing a slow decline after session 2 (figure 2).

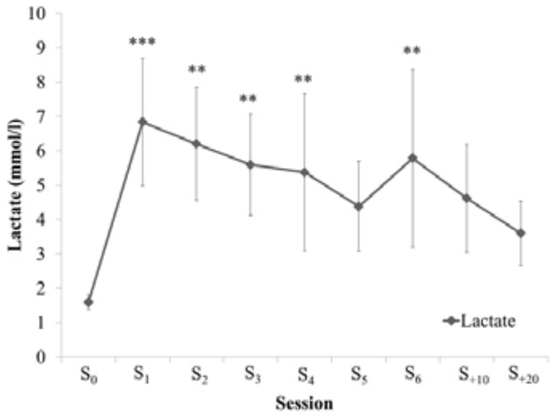


Figure 2. Blood lactate concentration recorded after each badminton session. Values are mean and standard deviation. A significant difference at the post hoc test with $S_0$ is indicated by *: P < 0.05; **: P < 0.01; ***: P < 0.001.

Height decreased in both SJ (-13% , $F_{8, 88}$ = 3.0281, $P$ < 0.001; $\eta^p$ = 0.226) and CMJ (-12% , $F_{8, 88}$ = 2.609, $P$ = 0.014; $\eta^p$ = 0.224) (figure 3). Mean height in SJ was lower than CMJ ($P$ < 0.001, 31.82 v 36.03 cm respectively). The peak power in SJ decreased (-5.87%, $F_{8, 88}$ = 2.379, $P$ = 0.024; $\eta^p$ = 0.209) and CMJ as well (-3.34%, $F_{8, 88}$ = 3.679, $P$ < 0.001; $\eta^p$ = 0.290). Moreover, the mean values of relative peak power revealed a higher ($P$ < 0.001) value during CMJ (47.21 W/kg) than during SJ (43.73 W/kg). There was a link between the power decrease in SJ and CMJ ($r$ = 0.872, $P$ < 0.001). LS showed an insignificant decrease, despite a -10% loss ($F_{8, 88}$ = 0.556; $P$ = 0.808).

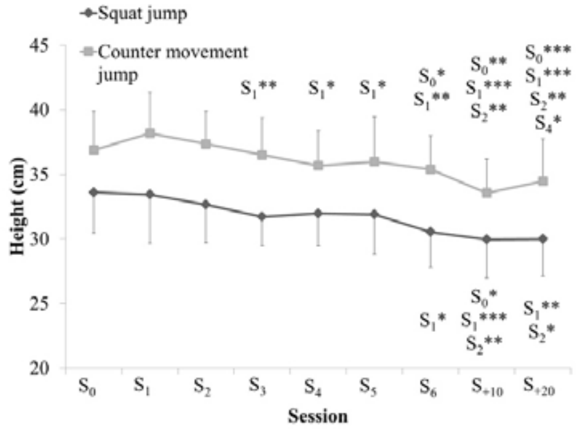


Figure 3. Squat and countermovement jump height recorded after each badminton session. Values are mean and standard deviation. A significant difference at the post hoc test with $S_0$ is indicated by *: P < 0.05; **: P < 0.01; ***: P < 0.001.

FG strength did not change ($F_{8, 88}$ = 1.006; $P$ = 0.439) whereas HG strength showed a decrease (-15%, $F_{8, 88}$ = 3.337; $P$ = 0.002; $\eta^p$ = 0.233) (figure 4), especially after 60 minutes of the game. There was a strong correlation between FG and HG strength ($r$ = 0.877; $P$ < 0.001).

The CPE increases ($F_{8, 88}$ = 30.480; $P$ < 0.001; $\eta^p$ = 0.813) and PPE ($F_{8, 88}$ = 17.367; $P$ < 0.001; $\eta^p$ = 0.713) during the entire match (figure 5).

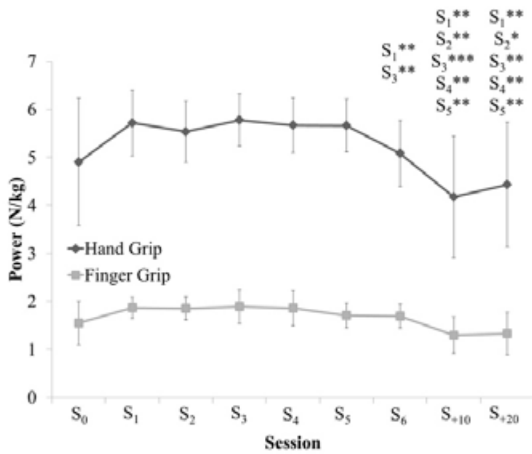


Figure 4. Hand- and finger-grip strength recorded after each badminton session. Values are mean and standard deviation. A significant difference at the post hoc test with $S_0$ is indicated by *: P < 0.05; **: P < 0.01; ***: P < 0.001.

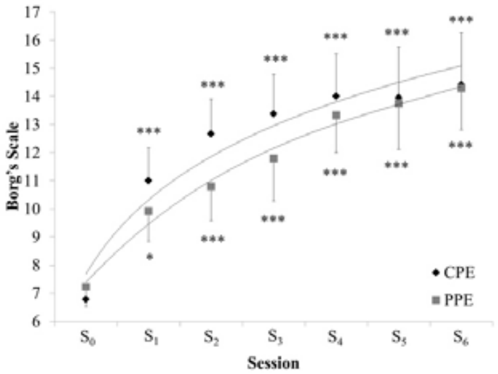


Figure 5. Central (CPE) and peripheral (PPE) perceived exertion rating recorded after each badminton session. Values are mean and standard deviation. A significant difference at the post hoc test with $S_0$ is indicated by *: $P < 0.05$; **: $P < 0.01$; ***: $P < 0.001$. A polynomial function is used for each $R^2$.

## Discussion

*Game characteristics*

The temporal characteristics in our experiment are in line with knowledge on the intermittent nature of the exercise performed (Wonisch, Hofmann, Schwaberger, von Duvillard, & Klein, 2003). Indeed, mean RD is about 7.6 s (Phomsoupha & Laffaye, 2015). However, RT (~8 s) is only half that measured during real matches (~15 s) and consequently, EPT (42%) was longer than reported in the literature with an average value of about 32.1%. This could be easily be explained by the advice given to the players to take as little RT as possible in order to fatigue their opponent. Despite this advice, the way RT was kept low was affected by the duration of the previous rally as revealed by the correlation (r = 0.554). Such a link between RD and RT has been previously observed with values ranging from r = 0.38 during the Olympics men's singles final (Laffaye et al., 2015) to r = 0.87 (Cabello & González-Badillo, 2003) during an international tournament, revealing the need to handle the metabolic and cardio-respiratory variables under relative fatigue threshold before engaging a new rally.

The surprising result is the high correlation between RT and SF (r = -0.881), showing that the time needed to rest was related more to the intensity of the rally than the duration. SF depends on the time the shuttlecock is kept in the air, and ranges from 0.92 $s^{-1}$ (Faude et al., 2007) to 1.3 $s^{-1}$ during the 2012 Olympics final (Laffaye et al., 2015). The link between SF and RT could reveal that a rally with high SF is the consequence of a high-intensity action of high muscular constraints and requires a longer RT.

The mean value of SF is ~1.0 $s^{-1}$, which is close to the value (1.021 $s^{-1}$) found in elite players by Phomsoupha & Laffaye (2015). The kinds of stroke used and the distribution in the way the point is won were similar in all sessions, meaning that the players continued to use the same tactics regardless of the fatigue. The only variable that decreased with fatigue was SF (-7%). In our study, the value decreased significantly from 1.06 to 0.97 $s^{-1}$, suggesting that the fatigue induced by the game impacted negatively on SF. Indeed, SF depends on either a change in the choice of serve or an increase in the duration of shuttlecock flight. To assess the impact on the serve on SF, we performed a complementary analysis by removing the serve from the recorded data. SF decreased in the same way from 1.03 to 0.96 $s^{-1}$ (-9.3%), revealing that if the long serve is overused at the end of the match to gain about 1.5 s at each serve, it is not the main explanation of the SF decrease. So, this could be explained by two factors: a higher shuttlecock trajectory, and a decrease in shuttlecock velocity, suggesting that the game characteristics of badminton strongly impact the energy required. The large number of powerful movements such as clears and smashes (n = 1246 and n = 925 respectively) increases the energy cost dramatically.

*Physiological responses*

Temporal characteristics showed that repeated high-intensity short rallies (5.8 ± 0.3 s) with numerous recovery periods (8.0 ± 0.3 s) lead to substantial mean BLa concentrations of 5.7 ± 0.8 mmol/l with concomitant high HR values (168.6 ± 12.2 beats/min). This is in line with the literature with mean value of 4.4 mmol/l for BLa concentration and about 170-180 beats/min for average HR (Phomsoupha & Laffaye, 2015). This corresponds to about 85%$HR_{max}$, which is slightly lower than values found in the literature, which is often over 90%$HR_{max}$ (Phomsoupha & Laffaye,

2015) in real conditions. Interestingly, the results indicated high heart rate values (~85%$HR_{max}$) throughout match play, probably induce the players' endurance capacities (57.4 ± 5.3 ml/kg/min), which may contribute to efficient BLa removal (Messonnier et al., 2001), faster reoxygenation of myoglobin, and, greater resynthesis of muscle phosphorylcreatine (Tomlin & Wenger, 2001). These physiological adaptations help to conserve the performance with muscle fatigue. In addition, the positive relationship between HR and SF values (r = 0.884) supports the hypothesis that the ability to regenerate phosphorylcreatine depends on oxidative processes and would be the main mechanisms maintaining neuromuscular performance.

Lower-limb neuromuscular responses

The peak power values found during SJ and CMJ (45.1 and 48.8 W/kg, respectively) are comparable to those found in a prolonged tennis match (Girard, Lattier, Micallef, & Millet, 2006) with 44.4 and 45.4 W/kg for SJ and CMJ respectively, but are higher than those found in a badminton match with elite players (about 30 W/kg) (Abián-Vicén et al., 2012). This difference could be explained by the methodological approaches, with the present study using the same formula and device as Girard et al. (2006) which overestimates the values when compared with a force plate, which was used in the study by Abián-Vicén et al. (2012). CMJ jump heights (~36 cm) is slightly lower than those found in national Spanish players (~39 cm in CMJ), probably due to the use of the arm movement in the aforementioned study.

Moreover, SJ and CMJ power decreases during the game (-5.87% and -3.34%, respectively). This decrease could be explained by a high number of jumps (n = 925) and eccentric movements to the net (n = 3170), which could induce damage in the muscular structure (Cress, Peters, & Chandler, 1992). In contrast, Abián-Vicén et al. (2012) did not find a significant decrease in the lower-limb force production during a 35 min of play whereas it lasted one hour in the present study. This suggests that muscle fatigue in the intermittent effort pattern of a badminton match occurs after ~50 minutes of play, which often happens, as shown from the analysis of the SuperSeries between 2007 and 2014. Indeed, 39% of all the matches exceed 45 min in men's single. This could be explained by the short RT between rallies (~8 s), which seems insufficient to recover adenosine triphosphate (ATP) and phosphocreatine (Glaister, 2005). Indeed, RT is a major determinant of high-intensity intermittent exercise to limit fatigue. Explosive lower-limb strength is not affected by a prolonged tennis game, in which the recovery duration between points represents 79% of the total duration (Girard et al., 2006), whereas it is affected in badminton with a 59% recovery duration in the present study. This suggests the key role of RT on ATP and phosphocreatine recovery.

Concerning LS, the mean value found at the beginning of the experimentation (60.8 kN/m) was higher than those found in the tennis literature, with values ranging from 18.2 kN/m to 34.8 kN/m in heterogeneous samples (Maquirriain, 2013). Part of the difference could be explained by the method used to measure stiffness; the other studies used either a force plate or ergo jump and Myotest systems have been shown to slightly overestimate (by about +8 kN/m) the LS value (Choukou et al., 2014). This high value may be explained by the increasing number of jump smashes, which solicits high visco-elastic properties of the lower-limb muscles; as well as the split step, which allows badminton players to behave like a spring by bouncing before moving in a chosen direction. Furthermore, to perform powerful strokes, kinematic analysis reveals that elite players use jumps to increase shuttlecock velocity (Cohen, Darbois-Texier, Quéré, & Clanet, 2015). This suggests that players adapt their spit step to receive shuttlecock at high velocity by reducing ground contact time and increasing LS.

LS remained unchanged with fatigue until the end of the match, despite a slight insignificant decrease (-10%). Such an insignificant decrease with fatigue has been noticed previously during sprint repetition (Choukou, Laffaye, & Heugas-De Panafieu, 2012) and prolonged tennis matches (Girard et al., 2006). The correlation observed between the decline in SJ and CMJ power with LS (r = 0.782 and r = 0.613, respectively) reveals that the ability to maintain a high level of force and power output is regulated by LS. This was previously considered as neuromuscular adaptation to fatigue (Choukou et al., 2012). The insignificant decrease in LS in correlation with a significant decreased in lower-limb power suggests that the central nervous systems modified the control pattern to maintain constant stiffness as previously shown in various motor tasks such as repeated sprint (Choukou et al., 2012) and to regulate movement reorganization under fatigue. Leg properties can be modified by stiffness regulation during SSC tasks, whereas the high number of motor units required jumping high during a SJ or a CMJ declines with fatigue.

*Upper-limb neuromuscular responses*

The value in our study of 44.2 ± 9.3 kg is close to that found in the study of Abián-Vicén et al. (2012) in male badminton (about 47 kg) and tennis players (between 46.5 and 61 kg) (Kafkas, Şahin Kafkas, Durmus, & Açak, 2014). This tends to prove that a threshold of grip strength is necessary to squeeze the racket using an isometric contraction during the stroke. During the game, the player has to squeeze the racket strongly for clears and smashes (≈2171 times).

During the match, HG strength increases to its maximal value after 10 minutes and decreases by -44.5% throughout the match. In the study of Abián-Vicén et al. (2012), HG value showed no difference before and after the game. This difference could be explained by two reasons. Firstly, the first test was done before the match, which is not the highest value measured during the match. Indeed, the best value occurs 10 minutes after the beginning of the match and not before it. This curious phenomenon could be explained by insufficient warm-up (Girard et al., 2006) or an increase in muscle temperature through an increased transmission rate of nerve impulses and decreased viscous resistance (Bishop, 2003). Secondly, our match lasted one hour, whereas in the previous study, the match was played under official conditions, which means the match duration was 35 min in men's singles. HG strength decreased after 50 min. This suggests that players are able to maintain a high level of isometric strength for the duration of a classic match time pattern of less than 35 min. This decrease could be explained by either pain on the lateral epicondyle of the elbow due to repetitive high-velocity arm movements (Kafkas et al., 2014) or the high number of maximal isometric contractions during powerful strokes (≈2171 representing 30.4% of strokes). This decrease in isometric strength could impact negatively on the way the racket is squeezed and consequently the hitting force (Kibler, Wilkes, & Sciascia, 2013). Shuttlecock velocity probably decreases and could be a plausible explanation for the decrease in SF. Indeed, we found a moderate but insignificant correlation between HG and SF decrease ($r = 0.543$), suggesting that the ability to squeeze the racket contributes moderately to stroke efficiency.

*RPE response*

Changes in RPE during a badminton match have never been investigated. CPE and PPE gradually increase throughout the match, whereas HR remains stable at high intensity. Such a dissociation has been observed previously during a prolonged tennis match (Girard et al., 2006), suggesting that cardiovascular stress is not the only contributor to RPE. Millet and Lepers (2004) suggest that the exercise induced muscle damage, and that eccentric contractions in particular contribute to RPE increase due to high leg muscle soreness. Indeed, studies have suggested that local muscle soreness due to eccentric contractions induce a stimulatory effect on ventilation increasing the perceived exertion (Davies, Rowlands, & Eston, 2009). The intense braking phase of the dominant leg during the net stroke can increase stress on the Achilles tendon by up to 6-12 times the player's body weight (Lee & Yoo, 2012) and up to five times for the knee patellar tendon (~3170 times during the game). Another explanation for the increase in RPE despite a constant HR value is related to a high level of mental resources used for self-regulation (self-control) affect (Muraven & Baumeister, 2000).

Implementation of high skilled cognitive activity such as optimal game tactics combined with high energy expenditure probably induced a significant level of self-control which can be defined by the way people regulate their thoughts, behaviour, negative affect and perception like fatigue (Muraven & Baumeister, 2000). Moreover, self-control has limited resources and is impaired by prior exertion reducing the capability for further self-control strain (Baumeister, Bratslavsky, Muraven, & Tice, 1998). By this way, the combination of cognitive and energetic demand through a match very probably impaired these limited mental resources and created difficulties to inhibit perceived exertion during the match. This impairment also known as ego-depletion state is very likely involved in the RPE augmentation along the match.

Prolonged periods of demanding cognitive activity also probably produced mental fatigue (MF) to the player (Marcora, Staiano, & Manning, 2009). During the match, MF increased and stroke production appeared much more difficult. MF influenced the perception of physical fatigue and should modify the perception of RPE throughout the match. Therefore, PPE and CPE increased while HR and neuromuscular variables remained unchanged.

## Conclusions

Players have a capacity to conserve a high intensity of performance despite a general fatigue state during 50 min before it declined. The metabolic fatigue is impacted more by the intensity of the stroke than the duration of the rallies. The rate of perceived exertion seems to be a combination of attentional and neuromuscular fatigue rather than metabolic fatigue. Consequently, in future studies, both researchers and trainers should consider the fatigue state as a means to increase players' abilities.

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# Speed and spin differences between the old celluloid versus new plastic table tennis balls and the effect on the kinematic responses of elite versus sub-elite players

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## Abstract

This study measured 1) the speed and spin differences between the old celluloid versus new plastic table tennis balls at pre ball-table impact and post ball-table impact when projected with topspin at 7.56 m.s$^{-1}$, and investigated 2) the effect this has on the kinematic responses of 5 elite versus 5 sub-elite players' forehand topspin in response to topspin and backspin. Plastic balls were lower in both speed and spin at pre and post ball-table impact compared with celluloid balls but the magnitude of change in speed and spin for each ball material differed. During flight before impact, plastic balls lost 3.98% more speed and 1.24% more spin than celluloid balls. Post ball-table impact, plastic balls showed a greater speed increment (0.69%) and smaller spin decrement (0.19%) than celluloid balls. Differences in players' kinematic responses to the different ball materials were found only when players returned backspin shots. Players supinated their rackets more by 2.23% at ball-racket contact and produced 3.37% less ball spin when returning plastic compared with celluloid balls; an indication of an early adaptation to the lower spin rate of plastic balls. The lack of differences in kinematic response to topspin may be due to the similar changes in speed and spin of both types of balls at ball-table impact. It is not known if a higher initial ball projection velocity would evoke differences in movement responses from the players post ball-table impact but could be explored in future studies.

Keywords: *Table-Tennis, Rule Change, Human Kinematics*

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## Introduction

Competitive table-tennis underwent a number of equipment changes over the last two decades that have affected game play (Takeuchi, Kobayashi, Hiruta & Yuza, 2002; Zhang & Hohmann, 2004). In the year 2000, the International Table Tennis Federation (ITTF) increased the diameter (38 mm to 40 mm) and mass (2.5 g to 2.7 g) of all competition balls. Mechanical testing revealed decreases in speed (1-2%) and spin (5-10 rps) of the 40mm compared with 38mm balls with no differences in deceleration when ejected by a machine (Iimoto, Yoshida, & Yuza, 2002; Tang, Mizoguchi, & Toyoshima, 2001). In actual game settings, rally time (3.1 s to 3.8 s) and lengths in the 1993 versus 2000 All Japan Championship competition increased for both men's (3.1 to 3.7) and women's (3.7 to 4.6) matches (Takeuchi et al., 2002).

More recently in 2014, plastic balls were introduced in all World Title and ITTF sanctioned events and the old celluloid balls were phased out due to environmental and cost concerns (ITTF, 2014). The ITTF reported that the new plastic balls were similar in weight and rebound properties as the old celluloid balls but were slightly larger in diameter and rounder (Küneth, 2017). Given the light-weight and low-density characteristics of table tennis balls, any changes in diameter and roundness to a ball are likely to affect its flight trajectory and the interactions between ball, table and racket.

The ITTF equipment committee conducted a mechanical test to investigate the horizontal and vertical rebound speed upon table impact after balls were projected onto a stationary racket with various rubber types. The plastic balls were found to have a higher vertical but lower horizontal speed than celluloid balls (Meyer & Tiefenbacher, 2012). While it is not clear what the initial conditions were and how flight characteristics were measured, Meyer and Tiefenbacher (2012) also found that velocity decreased more for the plastic than celluloid balls in flight. Inaba et al. (2017) investigated how the two balls differed pre and post ball-table impact by computing the coefficient of restitution and friction, and predicting the post impact trajectories through five velocity conditions with backspin applied. It was clear that the magnitude of differences between the two ball types depended on the initial conditions. The coefficient of restitution and friction of plastic balls were higher than celluloid balls with faster vertical and slower horizontal velocities respectively. At faster vertical speeds, akin to smashes, plastic balls were faster and rebounded higher compared with celluloid balls. At slower horizontal speeds, akin to serves, plastic balls were slower in speed and spin after table impact. It is not known if similar differences are present for topspin and sidespin shots as Inaba et al. (2017) only investigated backspin shots.

The flight and rebound differences between plastic and celluloid balls could affect game play. Anecdotal accounts collected from players by Meyer & Tiefenbacher (2012) suggested that they could sense that the plastic balls have less spin and speed than celluloid balls. However, it is unknown if those players, despite "sensing" a difference, had adapted their kinematic responses when returning an incoming plastic compared with celluloid ball. Players may adjust racket path, impact height, face angle and speed in response to ball kinematics changes (Iino, Mori, & Kojima, 2008). For example, when returning heavier backspin using forehand topspin, players opened their racket face angle more (more supinated) regardless of skill levels (Iino & Kojima, 2009). The elite players, however, were reported to accelerate the racket faster than sub-elite players when using the forehand topspin to cope with heavy backspins. Considering that different ball-flight characteristics yield different responses between elite and sub-elite table tennis players, it could also be anticipated that the larger and rounder plastic versus smaller and less round celluloid balls would evoke differential responses between players of different skill levels.

This study's first aim was to 1) mechanically test for any kinematic differences between plastic versus celluloid balls when fed by a machine in topspin mode only as backspin effects have previously been reported in the literature. The second and third aims were to 2) investigate the ensuing effects that the speed and spin differences between ball materials projected in topspin and backspin have on the forehand kinematic responses of table-tennis players and 3) how these may differentiate between elite versus sub-elite players. We hypothesized that 1) plastic balls would be slower in speed and spin during flight pre ball-table impact but faster in speed and spin and achieve a higher peak height than celluloid balls post ball-table impact when projected in topspin; where vertical velocity may be higher, such that coefficient of restitution of plastic balls is higher than celluloid balls. We also hypothesized that 2a) regardless of skill and spin, players would move closer to the edge of the table, reduce their racket angle (less supinated), and strike/return the plastic balls at a higher velocity and impact height compared with celluloid balls. This should result in the plastic balls being returned at a higher velocity with less spin compared with the celluloid balls. When responding to topspin, players were hypothesized to 2b) move further away from the table, reduce their racket angle, strike the balls at a lower velocity but higher hitting height, resulting in higher ball speed but lower spin rate, in response to plastic versus celluloid balls. When responding to backspin, players were hypothesized to 2c) move nearer to the table, reduce racket angle (less supinated) and strike the balls at a higher velocity, but lower hitting height, resulting in higher ball speed but lower spin rate, in response to plastic versus celluloid balls. Lastly, we hypothesized that 3a) elite players, regardless of spin or ball type, would strike the balls with greater racket velocity and spin, and 3b) display kinematic adaptations i.e. nearer hitting location to the table at a higher hitting height with a reduced racket angle compared with sub-elite players when returning plastic balls.

## Methods

### *Mechanical testing*

Mechanical testing was performed to investigate the kinematic differences between the newer plastic versus older celluloid balls during flight. Twenty-five balls of each material were used. Both ball types were consistent in brand (Nittaku), quality (3-stars) and colour (white). The balls were weighed using a precision balance (accuracy: 0.01 g; A&D, GF-2000, Japan) and measured using a standard Vernier calliper. A ball feeder machine (Newgy Industries Inc., Gallatin, TN, USA) was used to expel the balls with topspin at a fixed speed setting 9 ($7.56 \pm 0.20$ m.s$^{-1}$) at 1 s intervals to the table centre. The speed was decided after pilot testing revealed that this setting expelled the balls at a speed that was closest to actual serve speeds (Yoshida, Yamada, Tamaki, Naito, & Kaga, 2014) and the balls could consistently land on the same target area on the table. This was to ensure that differences found in the players' kinematics can be attributed more conclusively to the different ball types instead of other factors that cannot be controlled i.e. rubber, machine variability and so on. The middle 20 shots for each group of ball material were used for analysis i.e. 4th – 23rd as pilot testing indicated that the machine was less consistent when it first starts and at the end when there are fewer balls in the feeder storage. Ball kinematics were recorded at 2,000 frames per second using high speed cameras (i-SPEED, Olympus Corporation, Japan) at exit from the machine, pre and post ball-table impact (Figure 1). The first time-point when the ball exited from the ball feeder machine indicated the ball's initial kinematic properties. The ball's speed and spin towards the end of its flight were ascertained at pre ball-table impact. The ball's rebound characteristics were ascertained at post ball-table impact.

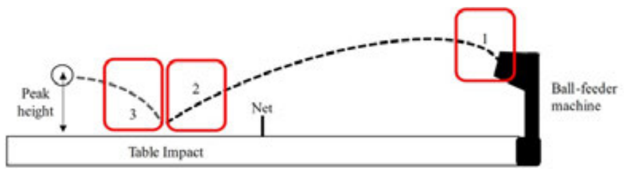


*Figure 1*. Mechanical Testing Set-up; red zones signify areas of data capture.

Ball spin rate was determined by measuring the time taken for an alphabet marked on the ball to move through 360 degrees or 1 revolution (Figure 2) (Inaba et al., 2017). Ball speed was measured by taking the distance travelled from the centre of the ball over 5 frames (0.0025s). Peak height post ball-table impact was measured from table surface to ball centre. All distances used were calibrated with the ball diameter at 40 mm as it is the most representative object of known dimension in the videos compared with the use of a conventional calibration pole. The authors acknowledge that there may be slight <1mm difference between ball materials that could affect the calibration but the ball's diameter still presented the best option for calibration as it is in the plane of movement. Videos were analysed using an open source video analysis software (Kinovea, version 0.8.15).

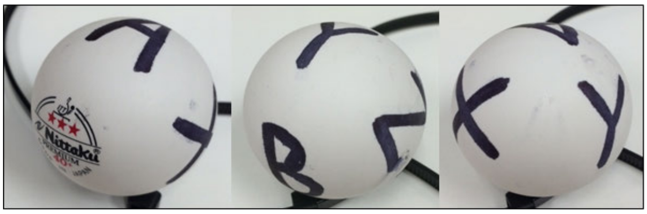

*Figure 2.* Alphabet markings on all balls used

A simple means comparison was performed rather than statistical analysis as the purpose was not to find any statistical difference but to assess if flight characteristics differed between the two ball types.

*Human testing*

### Participants

Five elite players from the national table-tennis team (age: 22.2 ± 4.2 years; playing experience: 18.3 ± 5.2 years; ITTF ranking: 64.4 ± 86.6; gender: 5 female) and five sub-elite players from the national youth intermediate training squad (age: 16.6 ± 2.5 years; playing experience 12.8 ± 5.4 years; ITTF ranking: 593 ± 390; gender: 4 males, 1 female) participated in the study. All players used the shake-hand grip and were offensive players except for one elite player who was a defensive chopper. None of the players had any injuries and had not started training with the plastic balls at the time of testing. Ethics approval was obtained by the Human Research Ethics Committee at the Singapore Sport Institute. Informed written consent was obtained from all players prior to testing.

### Apparatus

The same ball feeder machine was used to project balls in topspin and backspin respectively at speed setting 9 (7.56 ± 0.20 m.s$^{-1}$) at 1 s intervals to the players' forehand hitting position. These settings were similar to those used for the mechanical tests. Players had to respond using forehand topspin technique directed to a target area (0.3 x 0.3 m) straight down the table (Figure 3).

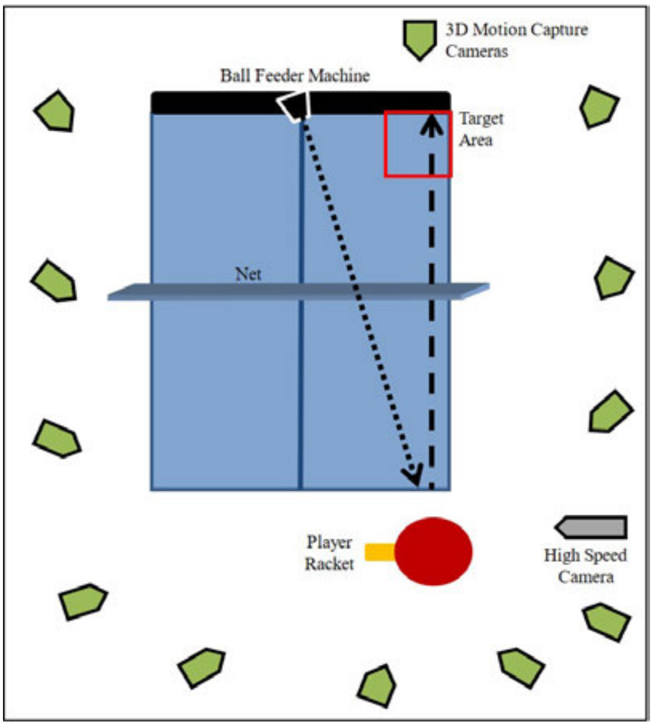


*Figure 3.* Experimental Set-Up

A 12-camera three-dimensional motion capture system (VICON MX series., Oxford, UK) captured the forehand topspin technique performed by the players at 500 Hz. Reflective spherical markers of 14 mm diameter were attached to the bilateral anterior superior iliac spines and bilateral posterior superior iliac spines (Figure 4) to define mid-pelvis of the players. This allowed the measurement of horizontal and vertical distances at racket-ball impact from the hitting side of the table-tennis table whereby the playing area was defined by four markers. Players used their own racket, where four reflective markers were attached to the lateral aspects, top and bottom of the racket to measure racket kinematics and racket-ball impact angle. The three-dimensional coordinates were expressed as a right-handed orthogonal reference frame fixed on the table (Z was vertical and pointed upwards, Y was horizontal and pointed to the centre of the target, while X was perpendicular to Y and Z). Selected racket kinematics, ball impact angle, ball impact height, and the perpendicular distances between players' mid-pelvis to the table at ball impact were computed and analysed. The high-speed camera was placed at point of racket-ball impact to record the ball speed and spin after racket impact.

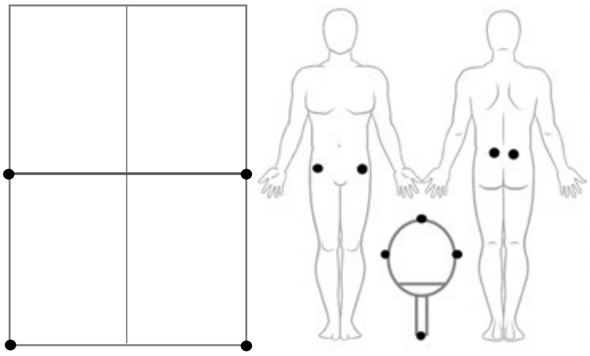

*Figure 4*. Reflective marker placement on subject, racket and table

## Procedure

Players were informed of the task procedures and marked up before performing five minutes of self-selected physical warm-up. Thereafter, each player underwent familiarisation whereby they had to perform forehand topspin at maximum strength to return 15 plastic and 15 celluloid balls that were delivered in topspin and backspin to the target area.

Upon completion of the familiarisation process, players rested for five minutes before actual testing. The four conditions of celluloid-topspin, celluloid-backspin, plastic-topspin and plastic-backspin were randomised and counter-balanced to avoid any sequence effects. Instructions were reiterated to hit each shot at maximum strength to the target area. Players were blinded to the ball type but not the spin that they had to return. Each player then performed 15 shots across four conditions totalling 60 shots. Before each set, LED lights were used to synchronise the high-speed camera and 3D motion capture system. Players rested for 2 minutes between sets while the ball-feeder machine was replenished with new balls.

## Variables and data processing

Five successful shots performed between the 3rd and 13th balls in each condition for each player were analysed to circumvent the inconsistency of the ball-feeder machine as mentioned earlier. The racket-ball impact frame was determined through synchronisation with the high-speed camera. At the impact frame, coordinates of the medial and lateral sides of the racket and pelvis were selected to calculate racket and pelvis centres. Hitting height from table was calculated from the z-coordinate of the racket centre, while racket-ball impact distance from the table was calculated from the y-coordinates of the pelvis centre and table. Racket speed was calculated by taking the displacement of one frame after racket-ball impact. Racket face angle was measured by using the y and z components of the two markers on the sides of the racket (Figure 5). Both S1 and S2 markers were projected in the YZ plane then an angle between the vector from S1' to S2' and Y axis in the global coordinate was defined as racket face angle.

$$\text{Assuming } x = 0, \tan\theta = \frac{z_1 - z_2}{y_1 - y_2}$$

$$\theta = \tan^{-1}\frac{z_1 - z_2}{y_1 - y_2}$$

The resulting displacement–time data of each marker was filtered using a Singular Spectrum Analysis. Optimal window sizes were chosen by comparing the residuals of the difference between filtered and unfiltered signals at several window lengths. Ball speed post racket-ball impact was measured by manual digitisation of the ball centre 5 frames after racket impact through the high-speed footages and the resulting displacement-time data of the ball centre were smoothed by using the simple moving average. Ball spin post racket-ball impact was also calculated by using high-speed footages by measuring the number of frames for the alphabet at point of racket-ball impact to complete 1 revolution, similar to the mechanical testing method that was previously described.

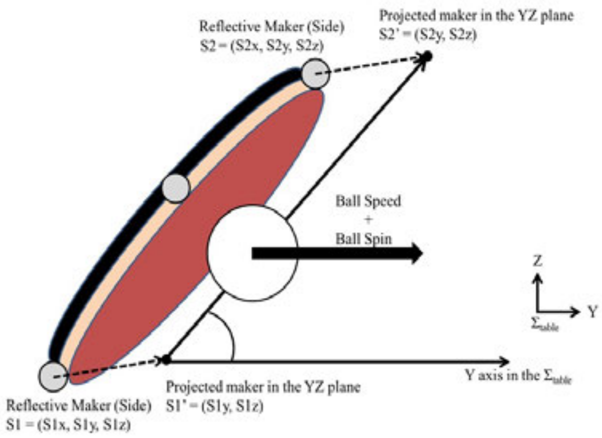


*Figure 5.* Racket angle calculation

All six variables from the human testing (racket speed and angle, hitting height and distance from table, ball speed and spin) were analysed using a 2 (ball types) x 2 (ball spin) x 2 (skill) mixed model analysis of variance (ANOVA). Main effects and interactions were subjected to Bonferroni post hoc tests and effect sizes were calculated using partial eta squared ($\eta p^2$) for omnibus comparisons. The level for significance was set at $p < 0.05$. Trends were reported when $0.05 < p < 0.08$. Small, medium and large effect sizes were defined as less than 0.2, between 0.2 to 0.5 and above 0.8 respectively (Cohen, 1988).

## Results

### *Mechanical testing*

Plastic balls were slightly heavier (0.006 g) and wider (0.7 mm) than celluloid balls (Table 1). Plastic balls had slower speed and spin during flight pre and post ball-table impact compared with celluloid balls (Table 2). During flight prior to ball-table impact, the decrease in speed (3.98%) and spin (1.24%) from that at machine exit was greater for plastic than celluloid balls. Post ball-table impact, plastic balls recorded marginally slightly faster speed increment (0.69%) and smaller spin decrement (0.19%) than celluloid balls. The peak height achieved by the plastic ball post ball-table impact was 1.1cm lower than the celluloid ball.

Table 1.
*Physical properties of balls.*

| | **Plastic** | **Celluloid** |
|---|---|---|
| **Mass (g)** | 2.754 (0.02) | 2.748 (0.01) |
| **Diameter (mm)** | 40.40 (0.06) | 39.82 (0.04) |

Table 2.
*Mechanical testing data*

| | **Plastic** | **Celluloid** |
|---|---|---|
| **1. Exit from machine** | | |
| Initial Speed ($m.s^{-1}$) | 7.56 (0.04) | 7.56 (0.06) |
| Initial Spin (rps) | 60.67 (0.18) | 62.57 (0.18) |
| **2. Before ball-table impact** | | |
| Speed ($m.s^{-1}$) | 5.53 (0.17) | 5.83 (0.13) |
| Spin (rps) | 57.25 (0.25) | 59.82 (0.50) |
| **Flight phase (time-point 1 to 2)** | | |
| Speed difference ($m.s^{-1}$) | - 2.03 | - 1.73 |
| Spin difference (rps) | - 3.42 | - 2.75 |
| **3. Post ball-table impact** | | |
| Speed ($m.s^{-1}$) | 6.27 (0.11) | 6.57 (0.14) |
| Spin (rps) | 46.30 (0.41) | 48.27 (0.57) |
| **Ball-table impact (time-point 2 to 3)** | | |
| Speed difference ($m.s^{-1}$) | + 0.74 | + 0.74 |
| Spin difference (rps) | - 10.95 | - 11.55 |

| | | |
|---|---|---|
| **Peak height after impact** | | |
| Height (cm) | 24.9 (1.5) | 26.0 (1.5) |

*Human testing*

Table 3 and 4 show the mean data for variables and the statistical output respectively from the human testing. There were trends with a large effect size whereby ball material affected the kinematics of the players but only when returning backspin shots (p = 0.058, $\eta p^2$ = 0.94). At racket-ball impact, players supinated the racket face by 2.09% more (p = 0.032) and produced 3.26% less spin (p = 0.01) after racket-ball impact when returning plastic compared with celluloid balls.

Spin types, independent of ball material, affected the kinematic responses of the players (p = 0.02, $\eta p^2$ = 0.97). When returning backspin compared with topspin, players contacted the ball 63.2% closer to the table (p < 0.01, $\eta p^2$ = 0.85) while producing 8.5% higher racket speed (p = 0.06, $\eta p^2$ = 0.39). Between skill levels, elite players supinated their racket face by about 17% more (p = 0.048, $\eta p^2$ = 0.41) than the sub-elites when hitting forehand topspin regardless of ball material and spin.

Table 3.
*Mean data for variables of forehand topspin*

| | Celluloid Ball | | | | | | Plastic Ball | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Backspin | | | Topspin | | | Backspin | | | Topspin | | |
| **Variables** | **All** | **Elite** | **Sub-Elite** | **All** | **Elite** | **Sub-Elite** | **All** | **Elite** | **Sub-Elite** | **All** | **Elite** | **Sub-Elite** |
| **Racket Speed ($m.s^{-1}$)** | 15.3 ± 0.84 | 15.0 ± 0.99 | 15.6 ± 0.62 | 14.1 ± 2.2 | 13.1 ± 2.8 | 15.0 ± 1.0 | 15.1 ± 0.68 | 14.8 ± 0.65 | 15.4 ± 0.60 | 14.0 ± 2.1 | 13.0 ± 2.6 | 15.0 ± 0.83 |
| **Hitting Location (m)** | 0.46 ± 0.33 | 0.33 ± 0.07 | 0.60 ± 0.44 | 1.00 ± 0.26 | 1.11 ± 0.22 | 0.89 ± 0.32 | 0.30 ± 0.07 | 0.26 ± 0.03 | 0.35 ± 0.08 | 0.99 ± 0.26 | 1.06 ± 0.19 | 0.92 ± 0.32 |
| **Hitting Height (m)** | 0.23 ± 0.04 | 0.23 ± 0.06 | 0.23 ± 0.29 | 0.25 ± 0.07 | 0.28 ± 0.05 | 0.21 ± 0.07 | 0.22 ± 0.04 | 0.22 ± 0.04 | 0.22 ± 0.05 | 0.22 ± 0.04 | 0.24 ± 0.04 | 0.21 ± 0.05 |
| **Racket Face Angle (°)** | 71.7 ± 7.35 | 75.9 ± 3.85 | 67.6 ± 8.00 | 68.1 ± 19.3 | 78.5 ± 23.0 | 57.7 ± 5.9 | 73.3 ± 7.53 | 77.1 ± 3.13 | 69.4 ± 8.97 | 68.0 ± 18.0 | 76.8 ± 22.2 | 59.1 ± 6.58 |
| **Ball Speed ($m.s^{-1}$)** | 15.6 ± 1.70 | 16.5 ± 1.45 | 14.8 ± 1.64 | 16.5 ± 3.20 | 17.0 ± 4.48 | 16.0 ± 1.53 | 15.5 ± 1.95 | 16.3 ± 1.42 | 14.8 ± 2.30 | 16.8 ± 3.36 | 17.1 ± 4.78 | 16.4 ± 1.47 |
| **Ball Spin Rate** (rps) | 113.5 ± 11.3 | 113.6 ± 8.21 | 113.4 ± 14.1 | 113.6 ± 13.6 | 106.3 ± 14.6 | 120.9 ± 8.20 | 109.8 ± 9.03 | 109.1 ± 7.66 | 110.4 ± 10.7 | 113.9 ± 18.4 | 104.4 ± 22.3 | 123.4 ± 6.45 |

Hitting height and locations are distances away from the table

Table 4.
*Statistical outputs of main effects*

| Results | df, df error | F | Significance (*p*-value) | Partial Eta Squared |
|---|---|---|---|---|
| **Ball Material** | 1, 8 | 3.22 | 0.18 | 0.866 |
| **Ball Spin** | 1, 8 | 17.2 | 0.02* | 0.972 |
| Racket Speed | 1, 8 | 5.05 | 0.06** | 0.387 |
| Hitting Location | 1, 8 | 46.59 | < 0.01* | 0.853 |
| Hitting Height | 1, 8 | 0.45 | 0.52 | 0.053 |
| Racket Angle | 1, 8 | 0.69 | 0.43 | 0.079 |
| Ball Speed | 1, 8 | 1.16 | 0.31 | 0.127 |
| Ball Spin Rate | 1, 8 | < 0.01 | 0.97 | < 0.01 |
| **Skill** | | | | |
| Racket Speed | 1, 8 | 2.52 | 0.15 | 0.239 |
| Hitting Location | 1, 8 | < 0.01 | 0.98 | 0.000 |
| Hitting Height | 1, 8 | 1.47 | 0.26 | 0.155 |
| Racket Angle | 1, 8 | 5.50 | 0.048* | 0.408 |
| Ball Speed | 1, 8 | 0.74 | 0.41 | 0.085 |
| Ball Spin Rate | 1, 8 | 3.05 | 0.12 | 0.276 |
| **Ball Spin * Ball Material** | 1, 8 | 8.06 | 0.06** | 0.942 |
| **Ball Spin * Skill** | 1, 8 | 0.55 | 0.76 | 0.524 |
| **Ball Spin * Ball Material * Skill** | 1, 8 | 1 | 0.55 | 0.667 |
| **Ball Material * Skill** | 1, 8 | 0.528 | 0.77 | 0.513 |

*: $p < 0.05$ (significant result)

**: $p \leq 0.06$ (close to significant result)

## Discussion

Celluloid table-tennis balls were switched to slightly larger plastic balls in the latest equipment rule change by the ITTF. Given the light-weight and low-density characteristics of table tennis balls, any changes in material, diameter and roundness to a ball is likely to affect its flight trajectory and the interactions between ball, table, racket and players' responses. This study aimed 1) to mechanically test for kinematic differences between plastic and celluloid balls when fed in topspin by a machine, 2) investigate the ensuing effects these may have when projected with both topspin and backspin on the forehand kinematic responses of table-tennis players and 3) how these may differ between elite versus sub-elite players. Hypothesis 1 was supported as plastic balls were slower in speed and spin than celluloid balls pre ball-table impact, but from pre to post ball-table impact, the speed increment was slighter faster and spin decrement was smaller for plastic than celluloid balls when projected in topspin. Hypothesis 2a and 2b were not supported as there were no kinematic differences found when players responded to the plastic versus celluloid balls in topspin. Hypothesis 2c was partially supported as players did produce less spin but supinated the racket more instead of less on plastic compared with celluloid balls when returning backspin shots. Hypothesis 3a was partially supported as elite players did not strike the balls with greater velocity nor spin but with a more supinated racket angle. Hypothesis 3b was not supported as the elite players did not display kinematic adaptations to the plastic balls when compared with sub-elite players.

The mechanical testing revealed kinematic differences between the plastic and celluloid balls during flight pre and post ball-table impact when projected with topspin. During flight pre ball-table impact, plastic balls recorded lower speed and spin compared with celluloid balls. This might be due to the increased diameter and weight of the plastic ball that in turn, increases the air drag experienced (Nagurka, 2003). While plastic balls did not record higher speed and spin post ball-table impact as hypothesized, the slight percentage increment in speed and smaller decrement in spin of plastic balls upon impact are still in line with previous theoretical prediction of a higher coefficient of restitution (Inaba et al., 2017). Based on the prediction of Inaba et al. (2017), a higher initial velocity may be able to elicit bigger differences between plastic and celluloid balls. The equipment used in the current study could only reliably project the balls at a speed of 7.56 $m.s^{-1}$ which may reflect the average velocity of a serve but not the forehand topspin at 17 $m.s^{-1}$ (Iino & Kojima, 2009). Future studies may include projections across a range of velocities to extend our understanding of the differences between the plastic versus celluloid balls.

Quantifying kinematic adaptations of players' responses to the new plastic versus old celluloid balls in light of its initial condition is important (Inaba et al., 2017) as it could present coaches and athletes with information to be strategic in technique and tactics modification (Hodges, 1993). Despite reported kinematic differences between celluloid and plastic balls (Inaba et al., 2017; Küneth, 2017; Meyer & Tiefenbacher, 2012), both elite and sub-elite players did not differentiate their forehand topspin return except in response to backspin shots whereby rackets were more supinated. The increased racket face angle resulted in less spin when returning the plastic compared with celluloid balls. First, the lack of kinematic differences when returning topspin could be associated with the mechanical testing result in this study where the change in speed and spin were similar at ball-table impact between the two ball materials. This means that both ball materials would have travelled towards the players with similar kinematic properties since the time from ball-table impact to players' racket-ball contact is short. Second, it could be possible that players responded differently to the plastic versus celluloid ball only in backspin because the plastic balls were likely slower and have less spin from a higher coefficient of friction due to the slower projected speed akin to serves; 6 $m.s^{-1}$ (Inaba et al., 2017). As such, players were able to supinate their racket more in response to the slower speed and spin, and thus produced less ball spin, perhaps with the intention to impart more force in the horizontal direction with less possibility of the balls going into the net or out of the table. Additionally, players did contact the plastic balls nearer to the table than celluloid balls by 0.16 m (34.7%) although this was not significant. Again, it is possible that if the range of projection velocities and spin rates increased, clearer kinematic adaptations can be elicited by maximising the effect of the coefficients of restitution and friction (Inaba et al., 2017).

Differences in kinematic responses of the players were found when they responded to the two ball spins regardless of ball types. When returning backspin versus topspin shots, players contacted the balls closer to the table and produced higher racket speed. Balls projected with backspin have a shorter trajectory due to the Magnus effect which explains the closer contact distance to the table. Previous research reported that when returning backhands against backspin versus topspin, the racket upward velocity at impact was higher for the former (Iino et al., 2008), similar to the higher racket speed in this study. Players potentially had to overcome the backspin by imparting greater speed to the ball to ensure that it crosses the net.

Racket and ball speed did not differentiate elite from sub-elite players in this study, which may be due to the sufficient time between each shot to generate their ideal racket speed. Iino and Kojima (2009) also did not find differences in racket speed between more well-trained versus less well-trained players but reported that advanced players required less time for racket acceleration despite covering a greater displacement which was in part contributed by a lower trunk axial rotation. Hence if time constraint similar to an actual game was present in this study, more kinematic differences may be found.

## Conclusion

This study assessed not only the differences in flight and rebound characteristics of the old celluloid versus new plastic balls when projected in topspin, but also the kinematic responses of elite versus sub-elite players' when performing forehand returns to backspin and topspin of both ball types. Plastic balls when projected with topspin at 7.56 m.s$^{-1}$, displayed similar trends to previously computed predictions (Inaba et al., 2017); slower in speed and spin in flight and slightly less change from initial properties at ball-table impact compared with celluloid balls. Kinematic differences in response to the different ball materials were found only when players returned backspin shots. Players supinated their racket more by 2.23% at ball-racket contact and produced 3.37% less ball spin when returning plastic compared with celluloid balls; an indication of an early adaptation to the lower spin rate of plastic balls by supinating the racket face more. The lack of movement difference in response to topspin may be due to the almost similar kinematic change of both balls at ball-table impact. A future study should be conducted whereby a range of ball projection velocities and response time could be included to better replicate the possible scenarios in an actual table-tennis game. This could be tied in with a performance analysis study to find out if actual game statistics have changed with the introduction of plastic balls. This study provides an early insight into the kinematic adaptations table tennis players have in response to the new plastic balls and could be used for the foundation of future studies and also for more targeted training.

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# Axis Specific Player Load to Quantify Lower Limb Biomechanical Loading in Adolescent Badminton Players

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## Abstract

While the use of accelerometer derived Player Load has become increasingly prominent, the limitation of this approach is that training load is reduced to a single number with no differentiation between the mechanisms of loading, resulting in a loss of context. As recovery from different loadings occur at different rates, the inability to differentiate between the loading mechanisms could lead to under or over training in one or more of these mechanisms. This study sought to compare axis specific accelerometer derived Player Load with differential RPE scores to establish a means of quantifying the lower limb biomechanical load of adolescent badminton training, to try and understand some of the context into the Player Load number. It was postulated that the Player Load from the vertical axis would provide a more precise measure of lower limb loading as other loading parameters, such as upper body rotation observed during a smash, would be removed from the calculation. Nineteen adolescent badminton players (Age: 14.0 ± 0.8 y) based at a dedicated high performance youth training environment wore a GPS-embedded accelerometer between the scapulae in a purpose built vest during court-based training. After each training session the participants provided two RPE scores, one localised for the legs and one for breathlessness. Overall low correlations were observed between the Player Load and RPE values. The Player Load for the vertical axis showed a stronger correlation with the RPE for breathlessness than the RPE for the lower limb stress. The results from this study suggest that axis specific Player Load from the vertical axis does not provide greater insight into lower-limb biomechanical load compared to overall Player Load in adolescent badminton players.

Keywords: *Badminton, Adolescent, Accelerometers, Training Load, RPE*

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## Introduction

Monitoring the loading experienced by an athlete during training or competition is essential for determining whether the athlete is adapting to a training programme, understanding the need for recovery and reducing injury risks (Bourdon et al., 2017). While an optimal "dose" of load will create adaptations that will result in performance improvement, too little will blunt adaptations and too much will result in overuse injury and illness (Vanrenterghem, Nedergaard, Robinson, & Drust, 2017). Furthermore, sudden spikes in load have been linked to injury occurrences across a range of sports (Gabbett, 2016). The need to manage loading in youth athletes is especially important as there is a growing body of evidence that has demonstrated an increase in overuse injuries amongst youth athletes and has linked inappropriate loads to injury and illness within this population (Murray, 2017). This evidence indicates that when dealing with youth athletes, planning appropriate loads and management of loading patterns is important to support a long sporting career (Bourdon et al., 2017).

The use of commercially available athlete tracking systems which incorporate GPS and inertial measurement units (IMUs) have become increasingly popular as a method of assessing athlete load. Catapult Innovations (Melbourne, Australia) developed a modified vector magnitude parameter called "Player Load" by integrating accumulated data from 3 accelerometers within the MinimaxX units (Boyd, Ball, & Aughey, 2011). In this context, Player Load is therefore the summed multidirectional acceleration and deceleration of a player's movements throughout a session. The Player Load calculation has been used in indoor court based sports where the use of GPS is not possible and the cost of local positioning systems (LPS) is prohibitively expensive (Cormack, Smith, Mooney, Yong, & O'Brien, 2013).

Player Load has been compared to internal load measures derived from heart-rate during badminton play (Abdullahi, Coetzee, & Van Dan Berg, 2019). This study found that Player Load was only correlated to the heart-rate measures at the high intensity zone but not at the low or medium intensity zones, with the latter showing a negative correlation. The authors concluded that while the high intensity movements in badminton, for example an overhead smash, would elicit a clear heart-rate response, 183.5 ± 5 beats.min-1 (Ghosh, 2008), the overall high work density observed in badminton compared to field based sports made it difficult to observe clear differences in the low and medium intensity zones. The limitation with this approach is that Player Load is reported as a single number with no way of differentiating how this load was accumulated. While "relative distance" was also reported, this metric equates the Player Load to a distance covered on a running track, an approach which may not be suitable for a court-based sport such as badminton.

Understanding how load is accumulated is important, as adaptations from different forms of loading occur in different timeframes. For example, recovery from physiological loading may take only a few hours for a well-trained athlete, while recovery from biomechanical loading may take a few days. A framework for differentiating between the physiological and biomechanical load was conceptualised by Vanrenterghem et al. (2017). The danger would occur when an athlete returns to training when recovered from the physiological load but under recovered from the biomechanical load, which may result in overuse injury. Conversely, if an athlete only continues physiological loading when fully recovered from the biomechanical load, the physiological system may be undertrained which would result in a performance decrement.

Within a youth population the management of biomechanical load is of particular importance as youth athletes are still developing fundamental movement skills and muscular strength. For example, a study of youth soccer players found that occurrences of knee valgus decreased with age and physical maturity (Read, Oliver, De Ste Croix, Myer, & Lloyd, 2018). In a badminton context, 64% of injuries recorded in youth players were soft-tissue sprains and strains with knee injuries being the most common, accounting for 42% of injuries to the lower limbs (Goh, Mokhtar, & Mohamad Ali, 2013). With this context, the measurement of lower limb biomechanical load would be essential in the prescription of optimal loading strategies for youth badminton players.

While the majority of studies report Player Load as a single score, Fish and Grieg (2014) reported in netball match-play the load separately for each of the acceleration axes. A similar approach may provide greater clarity as to how load is accumulated by youth Badminton players. Player Load from the vertical axis may provide a more precise measure of lower limb loading by removing other loading variables such as upper body rotation observed during a smash. Therefore, the purpose of this study was to evaluate whether Player Load from the vertical axis provides a more precise measurement of lower limb loading as compared to total Player Load or the Player Load from the antero-posterior and medio-lateral axis.

## Method

The participants for this study were 19 adolescent badminton players (age: 14.0 ± 0.8 years) based at a dedicated high performance youth training environment. The student-athletes were assessed over a 4-week period within which they would train twice a day from Monday to Friday and once a day on Saturday. Only court based training was assessed and gym based training was excluded. Each student-athlete wore a VX Sport (Visuallex Sport International, Lower Hutt, New Zealand) data logging unit (dimensions: 74 mm x 47 mm x 17 mm; mass: 50 g) between the scapulae in a purpose built harness during each court-based training session for the duration of the data collection. The VX Sport system has been found to possess both high intra-system and inter-system reliability with the Catapult Optimeye S5 system (Wylde, Lee, Low, & Callaway, 2018). However, to further limit any inter-unit reliability issues, the student-athletes wore the same unit throughout the assessment period. After each training session the student-athletes provided two rating of perceived exertion (RPE) scores (between 1 and 10, with 1 being low exertion), “RPE-L” being RPE localised for the legs and RPE-B being a rating for breathlessness (Weston, Siegler, Bahnert, McBrien, & Lovell, 2015). Prior to the data collections the student-athletes were briefed on the process and how to differentiate between the two RPEs, while pictures of lungs and legs were used in the record sheet to aide understanding (Figure 1).

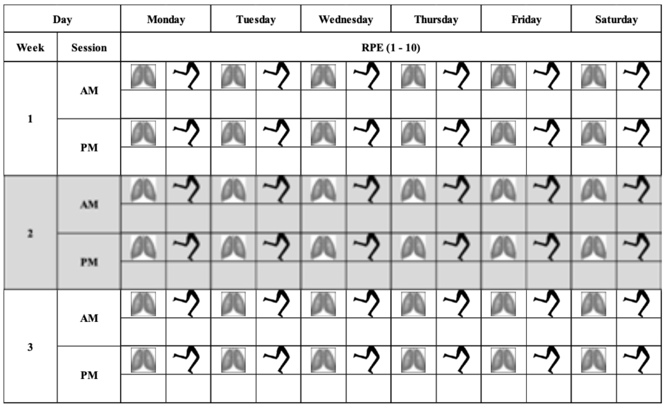


*Figure 1.* Differential RPE record sheet

After the completion of each training day, the accelerometer data were extracted at 100Hz using the accompanying VX Sport software. The raw data was filtered at 10Hz using a 3rd order Butterworth filter and centred mean in Matlab (MathWorks, Natick, MA, USA). The Player Load was calculated using a modified vector magnitude calculation, being the square root of the sum of activity counts squared (Boyd et al., 2011) (Equation 1) and the load for the vertical, antero-posterior and medio-lateral axis were also calculated (Equation 2).

$$Player\ Load = \sqrt{\frac{(ax_1 - ax_{-1})^2 + (ay_1 - ay_{-1})^2 + (az_1 - az_{-1})^2}{100}}$$

*Equation 1.* Total (Vector Magnitude) Player Load. Where a = accelerometer value; x, y, z represents the medio-lateral, anterio-posterior, and vertical axes respectively. The units of measurement are reported as arbitrary units (AU).

$$Vertical\ Load = \sqrt{\frac{(az_1 - az_{-1})^2}{100}}$$

$$Antero - Posterior\ Load = \sqrt{\frac{(ay_1 - ay_{-1})^2}{100}}$$

$$Medio - Lateral\ Load = \sqrt{\frac{(ax_1 - ax_{-1})^2}{100}}$$

*Equation 2*. Vertical, antero-posterior and medio-lateral load calculations.

To assess the sensitivity of the measures to differentiate between players of different capability, the players were split into two groups based on chronological age, "Lower Secondary" (aged 12 to 14 years) and "Upper Secondary" (aged 14 to 16 years). Cohen's Effect Sizes (Cohen, 1988) with modified descriptors (Hopkins, 2000) were used to assess the difference between the two groups. Pearson's correlation coefficient was used to assess the relationship between the various RPE scores and Player Load. Statistical computations were performed using SPSS v.24 (IBM Corp, Armonk, NY, USA) and statistical significance was accepted at $p<0.05$.

## Results

The descriptive data from the training sessions are outlined in Table 1. In general, there were "trivial" and "small" differences observed between the Lower Secondary and Upper Secondary groups. The only "moderate" effect size difference was observed for the Antero-Posterior Load and the RPE-L measures.

Table 1.
*Descriptive training load data per training session. AU= arbitrary units.*

| **Measure** | **All Age Groups (n=218)** *Mean ± SD* | **Lower Secondary (n=85)** *Mean ± SD* | **Upper Secondary (n=133)** *Mean ± SD* | **Effect Size** *Lower Sec vs. Upper Sec* |
|---|---|---|---|---|
| Duration (min) | 113.83 ± 39.08 | 112.48 ± 40.43 | 114.69 ± 38.33 | Trivial |
| Total Load (AU) | 1678.91 ± 700.01 | 1441.19 ± 552.38 | 1830.83 ± 742.79 | Small |
| Vertical Load (AU) | 989.92 ± 442.84 | 863.67 ± 356.27 | 1070.6 ± 474.13 | Small |
| Antero-Posterior Load (AU) | 815.04 ± 372.97 | 680.24 ± 310.3 | 901.19 ± 385.02 | Moderate |
| Medio-Lateral Load (AU) | 713.55 ± 305.62 | 610 ± 228.42 | 779.73 ± 330.19 | Small |
| RPE-L (AU) | 6.83 ± 1.55 | 7.41 ± 1.31 | 6.47 ± 1.57 | Moderate |
| RPE-B (AU) | 6.53 ± 1.63 | 7.08 ± 1.3 | 6.18 ± 1.73 | Small |

The correlations were mostly found to be significant at $p<0.05$ (Table 2). Stronger correlations were observed when both the Lower Secondary and Upper Secondary groups were viewed in isolation. In the Lower Secondary group, the strongest correlation was observed between Vertical Load and RPE-L, while for the Upper Secondary group the strongest correlation was observed between Total Load and RPE-B.

Table 2.
*Pearson correlation coefficient between Player Load and differential RPEs*

| | Total Load | Vertical Load | Antero-Posterior Load | Medio-Lateral Load |
|---|---|---|---|---|
| **All Age Groups (n=218)** | | | | |
| RPE-L | 0.126* | 0.134* | 0.095 | 0.086 |
| RPE-B | 0.180** | 0.182** | 0.159* | 0.121* |
| **Lower Secondary (n=85)** | | | | |
| RPE-L | 0.235* | 0.244* | 0.200* | 0.185* |
| RPE-B | 0.163 | 0.191* | 0.164 | 0.035 |
| **Upper Secondary (n=133)** | | | | |
| RPE-L | 0.223** | 0.208* | 0.199* | 0.182* |
| RPE-B | 0.312** | 0.285** | 0.294** | 0.268** |

* Significance of $p<0.5$ ** Significance of $p<0.05$

## Discussion

The correlations between Player Load and differential RPE, although significant, were low which is consistent with the findings from the study of Australian Football, where "trivial", "small" or "unclear" were observed between the player load values and the differential RPEs (Weston et al., 2015). In this study the RPE-B value, which represented the participants' perceived breathlessness, were more highly correlated to the Player Load compared to the RPE-L, which represented the lower limb biomechanical load. Contrary to the expectations of this study, the Vertical Load was more strongly correlated with the RPE-B and not RPE-L.

While session RPE has been shown to be a valid form of quantifying training load in youth athletes (Haddad et al., 2011; Padulo et al., 2014), it has been observed that youth athletes with greater training experience are able to more accurately perceive exertion compared to youth athletes with less experience (Barroso, Cardoso, Carmo, & Tricolo, 2014). Therefore, it was assumed that the older group (Upper Secondary), with a longer training history, would provide more reliable RPE scores compared to the younger and less experienced group (Lower Secondary). In this study, the Upper Secondary group demonstrated a stronger correlation between the Player Load and the RPE-B values, while in contrast the Lower Secondary group recorded stronger correlations between the Player Load and RPE-L values. The Lower Secondary group was the only instance where the strongest correlation was between the Vertical Load and the RPE-L values.

While the use of RPE to quantify training load has been validated in tennis (Gomes, Moreira, Lodo, Capitani, & Aoki, 2015), a study of elite junior tennis players highlighted the complexity of load perception (Murphy and Reid, 2013). In this study, the session RPE and drill RPE of junior tennis players during training were compared to the expected session RPE and drill RPE as rated by their coaches. While there were high levels of agreement between actual and expected drill RPE, there were significant differences between the actual and expected session RPE. This study highlighted that for junior tennis players the total session RPE is greater than the sum of the RPE of the individual drills. In a badminton context, explosive lower limb movements observed during training (jumps, lunges etc.) would create high Vertical Load and high RPE-L values. By contrast, holding a low position (isometric squat) while waiting for an opponent's shot, would produce low Vertical Load but potentially high RPE-L values. These "low load, high RPE" movements may explain the difference between the Vertical Load and RPE-L values found in the current study, as the total lower limb exertion of the session (RPE-L) is greater than the sum of the explosive lower limb movements (Vertical Load) within the session.

The reporting of loads from the individual axis is currently not common place and the results from this study suggest that this approach may not provide any greater resolution to differentiate between lower limb and other types of loading for youth badminton players. In badminton match play, the lunge accounts for 15% of movements and produces high forces experienced in the lower limbs (Kuntze, Mansfield, & Sellers, 2009). Youth athletes have been shown to be inefficient in utilising the impact forces of the lunging movement in a Squash context (Williams and Kuitunen, 2010) emphasising the importance of understanding the loading associated with this movement. In a lunging movement the upper body does not remain upright meaning that the vertical axis of the accelerometer, when placed between the scapulae, is no longer aligned to the direction of the vertical force.

A novel approach has been devised for measuring loading of overhead strokes in badminton, combining video-based time-motion analysis and accelerometry (Saski, Nagano, & Ichikawa, 2018). In this approach, movements with a load of greater than 4 g were isolated and manually classified based on the video of the movement. While this approach provided insights into the loading of single leg landings during overhead strokes, the authors acknowledged the arbitrary nature of the 4 g cut-off. In addition, the type of video-based time-motion analysis used in this study has been found to be labour intensive (Dobson and Keogh, 2007) and time-consuming (Jarning, Mok, Hansen, & Bahr, 2015), meaning that it may not feasible to use this approach for monitoring of load in daily training for a large group of athletes.

Only readings from the accelerometer are used in the calculation of Player Load, the orientation of the unit in relation to the athlete during movement is not accounted for. This is not an issue when reporting total Player Load as data from all axis are combined during the calculation but becomes apparent when looking at the load for each axis in isolation. Combining readings from the accelerometer and gyroscope within the IMU may provide greater resolution regarding the type of loading being experienced. In Cricket fast bowling, McNamara, Gabbet, Chapman, Naughton, & Farhart (2015) were able to use measures from the accelerometer and gyroscope to differentiate between bowling and non-bowling actions. In addition, the application machine learning in a sport context is increasing able to identify specific movements using data derived from IMUs (Crust, Sweeting, Ball, & Robertson, 2018). While such a machine learning approach has been used in badminton (Anand, Sharma, Srivastava, Kaligounder, & Prakash, 2017), this was from using two wrist worn IMUs to identify stroke type (serve, clear, drop or smash). Further research is required to understand if these approaches could be applied in badminton to highlight movements, such as lunges and smashes, using a single trunk mounted IMU and then calculate the load generated by these movements. Such an approach would provide greater resolution and may provide an improved solution for measuring lower-limb loading in badminton.

## Conclusion

This study sought to use differential Player Load scores and RPE to quantify lower limb load in the adolescent badminton players. Significant but low correlations were found between the Player Load and the differential RPEs. The Vertical Load did not provide any greater insight into player loading than the total Player Load variable. When the participants were split based on chorological age, both the Player Load and the Vertical Load for the younger players was more strongly correlated to the RPE-l score while for older players they were more strongly correlated to the RPE-B score.

It is suggested that the reasons for these findings are that "low load, high RPE" movements (such as the isometric squat) are not well represented by the Player Load calculation and the vertical axis of the accelerometer is not aligned to the direction of the Vertical Load during key movements, such as lunges and smashes. As such, this does not provide of true representation of the Vertical Load created during these badminton specific movement. It is therefore proposed that a machine learning approach, which utilises both the accelerometer and gyroscope data from a single trunk mounted IMU, may provide an improved solution to attribute load to difference types of badminton specific movement and warrants further investigation.

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# Is the level of eye-hand coordination and executive functioning related to performance in para table tennis players? – An explorative study

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## Abstract

The goal of this explorative study was to explore whether eye-hand coordination and executive functions (i.e. cognitive flexibility, attention control and information processing) are related to the performance level in para table tennis players. The data of 11 elite (age 15-54) and 11 non-elite para table tennis players (age 13-49) were analyzed. The results showed that the elite players performed better than the median norm values for cognitive flexibility and attention control while the non-elite players demonstrated slower information processing than the median norm values ($p<0.05$). The players' competition rating correlated significantly with the eye-hand coordination, cognitive flexibility and information processing measures ($p < 0.05$). Players with a competition rating > 1000 points scored ≥ 24 catches per 30 s in the eye hand coordination task, whereas the players with < 1000 rating points score ≤ 18 catches per 30 s. In contrast, there was a clear overlap of scores between the players with > 1000 and < 1000 rating scores in the executive functions tests. The results present a first profile of para table tennis players regarding their eye-hand coordination and executive functions and the relationship of these constructs with the performance level. Long-term international cooperation is recommended to understand the value of the measured constructs to predict future successes.

Keywords: *Sports for Persons with Disabilities, Psychomotor performance, Mental Processes, Aptitude*

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## Introduction

The 2016 Paralympic games in Rio de Janeiro hosted 29 medal events for individuals and teams in para table tennis. This relatively high number of medals to distribute is mainly due to the diversity of the players' impairments; para table tennis includes eleven different sport classes (Table 1) (International Table Tennis Federation, 2018). Players that compete while sitting participate in classes 1 to 5, those who are able to participate standing play in classes 6 to 10. Players with an intellectual impairment participate in class 11. The para table tennis player's classification is allocated through an evaluation before competition by a group of classifiers who are trained and certified by the International Table Tennis Federation. This evaluation may include but is not limited to physical, technical and observation assessments both off - and on- table. More awareness to the Paralympic performance from the spectrum of recreational sport participation to elite level (Blauwet & Willick, 2012) in combination with the many classes to win a medal in para table tennis, resulted in more attention for para talent programs from national table tennis associations.

The national associations are aiming to find high potential para players and support them with training facilities and personal coaching to improve their success rate. It is a challenge to reveal the determinants that predict future elite performance in para table tennis players, as it is for able bodied table tennis players, since many factors play a role (Elferink-Gemser, Jordet, Coelho E Silva, & Visscher, 2011; Faber, 2016; Gagné, 2004). Similar to the talent identification challenges encountered for typical developing players, one is searching for the performance characteristics that are needed to excel. As para table tennis deals with a relatively small and heterogeneous population of players with a large variety of impairments due to e.g. neurologic, systematic or traumatic conditions, the exploration of these performance characteristics is not easy. Still, it seems worth searching for the key-factors of success to identify players with high potential and connect them to the opportunities for developing their talent.

Table tennis is recognized as one of the fastest sports in the world in terms of game-speed (Abernethy, 1991; Lees, 2003). Although no scientific evidence was found, and this may vary between classifications, it seems likely that elite para table tennis players generally do not reach the same game-speed as in typical table tennis play at the elite level, and rally lengths might also be different and even vary between classes (Fuchs, Faber, & Lames, 2019). Nevertheless, elite para table tennis players still need to perform a combination of mainly open complex motor skills and tasks under constantly changing conditions with a similar physiological load as in typical table tennis players regardless of their classification (Kondrič, Zagatto, & Sekulić, 2013; Schmidt & Lee, 2011). It is likely that the disabilities in para table tennis players will hinder the execution of the intended movements and reaction times to a certain extent while influencing the player's tactical strategies (Kannekens, Elferink-Gemser, & Visscher, 2011; Munivrana, Furjan-Mandić, & Kondrič, 2015). Consequently, the time frame to respond in para table tennis is still considered relatively short which appeals to a player's processes responsible for purposeful, goal-directed behavior. To explore the parameters that might be associated with high or low performance, it is hypothesized that in each of the para table tennis classes the success of a player is related, at least to a certain extent, to his or her perceptuo-motor and executive functioning capacities.

Recent studies in typically developing table tennis players have produced some interesting results regarding the importance of perceptuo-motor skills for performance. It was found in a prospective study that perceptuo-motor tests assessing ball control could predict future performance in youth table tennis players ($R2 = 51\%$, $p < 0.001$) (Faber, Elferink-Gemser, Faber, Oosterveld, & Nijhuis-Van der Sanden, 2016). These tests focused on the assessment of eye-hand coordination while handling a ball (e.g. aiming, dribbling, throwing and catching). This perceptuo-motor ability also appears to discriminate between high and low potential youth players (Faber, Oosterveld, & Nijhuis-Van der Sanden, 2014). These results are in line with the outcomes of other studies in table tennis and tennis demonstrating that eye-hand coordination is essential ability for high performance in racket sports (Mantis, Zachopoulou, & Mavridis, 1998; Nikolić, Furjan-Mandić, Kondrič, 2014; Filipčič & Filipčič, 2005; Filipčič, Pisk, & Filipčič, 2010). Regarding para table tennis as a complex motor task, it has many similarities to the challenges in table tennis for typical developing players. In all classifications, most players use their hand to hold the bat and hit the (upcoming) ball under various conditions (e.g. rotation of the ball and speed). Only for some small number of players that use other parts of the body, for example their mouth, to hold the bat this may not be the case. Thus, the level of eye-hand coordination function might be associated with performance in para table tennis players.

A player's level of executive functioning is also likely to be related to table tennis performance. This applies to the regular game of table tennis as well as para table tennis as players need to perform under severe time constraints in changing and unpredictable situations which require a higher level of executive functions in order to be successful (Raab, Masters, & Maxwell, 2005; Walsh, 2014). Executive functions enable goal-directed, future-oriented behavior (Alvarez & Emory, 2006) as they are essential for the synthesis of external stimuli, formation of goals and strategies, preparation for action, and verification that plans and actions have been implemented appropriately (Diamond, 2006; Miyake et al., 2000). These are all ingredients of the task 'table tennis' in every match and is considered independent of the classification within para table tennis.

Specifically, the player's cognitive flexibility, attention control and information processing are suggested to be directly related to (para) table tennis performances (Abernethy, 1991; Ak & Koçak, 2010; Anderson, 2002; Hung, Spalding, Santa Maria, & Hatfield, 2004; Wang, Guo, & Zhou, 2016). Cognitive flexibility reflects a player's capacity to adapt quickly to the continuously changing situations (e.g. variations in rotation and speed of the upcoming ball) during a game by initiating creative alternative solutions while learning from mistakes (creativity, working memory and cognitive shifting) (Monsell, 1996). Attention control allows a player to concentrate on each forthcoming rally (selective attention) and to suppress ongoing or planned but inappropriate actions in a given situation (inhibition) (Logan, 1994). The latter might happen when an unexpected service or return (e.g. variation of spin or location) is played by the opponent or the ball hits the net which influences the flight of the ball. A higher level of information processing refers to the ability to generate fast reaction times and psychomotor responses (fluency), which is suggested to accompany better performance in (para) table tennis (Hughes, Bhundell, & Waken, 1993). Cognitive flexibility and attention control are also termed the 'higher-level' cognitive functions and are involved in the control and regulation of the 'lower-level' cognitive functions e.g. information processing (Diamond, 2006; Sanchez-Cubillo et al., 2009). Considering the task constraints within the game of para table tennis, it seems logical that executive functions are even more important for performance because para players need to deal with personal constraints reducing the number of potential strategies. The connection between executive functions and performance in para table tennis is supported by studies in typical table tennis and other open complex ball sport that confirm the relationship between the level of executive functioning and performance (Huijgen et al., 2015; Verburgh, Scherder, van Lange, & Oosterlaan, 2014; Vestberg T, Gustafson, Maurex, Ingvar, & Petrovic, 2012; Wang et al., 2013; Wang, Guo, & Zhou, 2016). These studies showed that elite (youth) players outperformed their sub-elite or non-elite peers regarding cognitive flexibility and attention control. Though, at this moment there are, to the best of our knowledge, no studies evaluating the executive functions in para table tennis players (classification 1-10).

The present study aimed to explore the relationship between eye-hand coordination and executive functions and the level of table tennis performance in para table tennis players (classification 1-10). Although it was clear that we needed to deal with a rather small and heterogeneous population in para table tennis including different classifications, the approach of this first study concerning provides a model for gaining insights into the factors that determine performance in para table tennis. For this purpose, the level of eye-hand coordination and executive functioning of para table tennis players was first individually profiled and compared to the norm population (when available) while taking age and sex into account. Second, the association between the level of eye-hand coordination and executive functioning and the players' table tennis performance was explored.

## Methods

### *Study design*

A cross-sectional study design was used to explore the eye-hand coordination and the executive functions in para table tennis players. The study protocol and informed consent procedure were approved by the Ethics Committee of the Medical Spectrum Twente (Medical School Twente, Institute for Applied Science, Enschede, the Netherlands; METC/13053.fab 19-2-2013) in full compliance with the Declaration of Helsinki. Written informed parental consent and player assent were obtained for all players under the age of 18 years. Written informed consent was obtained for all adult players.

### *Participants*

Para table tennis players from different training/playing levels were recruited with support from the Netherlands Table Tennis Association's coaches of the Paralympic division. Some of the recruited players were from the national para table tennis training group and were proven or expected by expert national coaches to become successful at the international para table tennis level. They were all ranked in the top 2 of their classification category. This subgroup was called the elite group or elites. The other recruited players only trained at their local club and were not expected to be selected for a talent program and/or reach international level. This subgroup was called the non-elite group or non-elites.

The data of 22 para table tennis players including 11 elite players (age 15-54 years; 9 males and 2 females) and 11 non-elite players (age 13-49 years; 8 males and 3 females) were analyzed in this study (Table 1). All players were officially classified into a sport class matching their function level. Four elite players and 7 non-elite players were sitting in a wheelchair when playing table tennis. All the others play table tennis while standing. The underlying causes of the players' impairments were diverse and contained both neurological (e.g. cerebral palsy, spina bifida, spinal cord injury and brain trauma) and orthopedic (e.g. clubfeet, scoliosis, growth deficits) conditions or a combination. The elite and non-elite group contained 3 and 4 players with brain damage (i.e. cerebral palsy or brain trauma), respectively. The elite group showed significantly higher competition rating scores ($p < 0.001$), training hours per week ($p < 0.003$) and total training volumes ($p < 0.002$) than their non-elite peers.

### *Measurements*

#### **Eye-hand coordination**

Eye-hand coordination was assessed using the eye-hand coordination test item of the Dutch perceptuo-motor skills assessment (Faber et al., 2016; Faber et al., 2014). The standardization of the test is captured in a protocol (Faber et al., 2016). During the eye-hand coordination test players need to throw a ball at a vertically positioned table tennis table at 1-meter distance with one hand and to catch the ball correctly with the other hand as many times as possible in 30 s. A modification on the original protocol was introduced for the players who lacked function of upper extremity of one side of the body to catch the ball as a consequence of his / her disability (e.g. unilateral spastic paralysis due to cerebral palsy). In these cases, players were allowed to use one hand to throw and catch the ball. The best number of correct catches from two attempts was recorded as raw outcome score. Since no norm values are available, it was not possible to convert the raw scores into scaled or percentile scores. The reproducibility of the eye-hand coordination test is considered satisfactory (ICC 0.91; 95% confidence interval 0.85-0.95; $p < 0.001$); CV 7%) (Faber, Nijhuis-Van Der Sanden, Elferink-Gemser, & Oosterveld, 2015).

Table 1.
*Characteristics of the included para table tennis players*

| | | Total | Elite | Non-elite |
|---|---|---|---|---|
| N | | 22 | 11 | 11 |
| Age (years) | | 27 (13-54) | 23 (15-54) | 39 (13-49) |
| Sex (n) | Male | 17 | 9 | 8 |
| | Female | 5 | 2 | 3 |
| Brain damage (n) | | 7 | 3 | 4 |
| Classification (n) | Wheel-chair bounded | 11 | 4 | 7 |
| | 1 | 1 | - | 1 |
| | 2 | 3 | 2 | 1 |
| | 3 | 1 | - | 1 |
| | 4 | - | - | - |
| | 5 | 6 | 2 | 4 |
| | Standing | 11 | 7 | 4 |
| | 6 | - | - | - |
| | 7 | 3 | 3 | - |
| | 8 | 3 | 2 | 1 |
| | 9 | 2 | 1 | 1 |
| | 10 | 3 | 1 | 2 |
| Competition rating score (points)* | | 705 (0-2252) | 1317 (636-2252) | 472 (0-1006) |
| Training (hours/week)* | | 10 (1-20) | 18 (6-20) | 5.5 (1-14) |
| Training volume (hours)* | | 1500 (40-7800) | 2280 (240-7800) | 740 (40-2200) |

Age, rating, training and training volume are presented in medians and ranges. Other data are frequencies. *$p < 0.01$ showing a significant difference between the elites and non-elites.

### Executive functions

The executive functions of cognitive flexibility (creativity, working memory and cognitive switching), attention control (inhibition) and information processing (psychomotor response) were assessed in all participating players. To cover all constructs a combination of three tests was used: The *D-KEFS Design Fluency test*, the *Trail Making test* and the *Stroop test*. In all tests, raw scores were determined and converted into scaled or percentile scores based on the available norm values that include a correction for age and sex. Validity and reliability are reported to be satisfactory for all executive measures (McLeod, Barr, McCrea, & Guskiewicz, 2006; Strauss, Sherman, & Spreen 2006; Swanson, 2005).

The *D-KEFS Design Fluency test* is a standardized test and measures cognitive flexibility and attention control (Delis, Kaplan, & Kramer, 2001). The task is administered with pen and paper and consists of three conditions: 1) filled dots, 2) empty dots, and 3) switching. In the first condition, a sheet with squares containing with five filled dots is presented to the participant. The participant is asked to draw as many unique designs as possible in 60 seconds using four straight lines in each square to connect the dots (creativity and working memory). In the second condition the squares contain five filled dots and five empty dots. The participant is instructed to use the empty dots to connect the four lines, and ignore the filled dots (creativity, working memory and inhibition). The third condition consists of squares containing five filled dots and five empty dots as well.

In this condition, the participant is instructed to alternate between the filled and empty dots when drawing the designs, so that each line is drawn between a filled and an empty dot (creativity, working memory and cognitive switching). For each condition the total number of correct, unique designs was determined and used as raw score. The higher number of designs, the better a player's executive functions. The raw scores of each condition were converted into scaled scores based on the manual's norm values (Delis et al., 2001). A scaled value of 10 represents the $50^{th}$ percentile score with 3 points counting as one standard deviation. The sum of the scaled scored of all three conditions was calculated as a total score, which was also converted into a scaled score. To obtain a more specific score for the players' cognitive switching ability a contrast score was calculated by subtracting the combined scaled score of condition 1 and 2 from the scaled score of condition 3. This contrast score was again scaled based on the norm values.

The *Trail Making test* is a paper-and-pencil task that measures cognitive flexibility and information processing and has two conditions: 1.) Trail A, a number-sequencing task and 2.) Trail B, a number-letter switching task (Reitan, Kaplan, & Kramer, 1971). Trail A consists of encircled subsequent numbers from 1 to 25 placed on a paper. Participants are asked to connect the dots in numerical order as quickly as possible by drawing a line from one dot to the next (psychomotor response). Trail B consists of encircled numbers (1 to 13) and encircled letters (A to L). In this condition, participants need to connect the dots as quickly as possible while alternating between a numerical and an alphabetical order (i.e. 1-A-2-B-3-C-4-D-5-E and so on) (cognitive flexibility). Time-durations in both conditions were measured in seconds and used as raw scores and converted into percentile scores (Tombaugh, 2004). Faster times reflect a higher level of information processing (Trail A) and cognitive flexibility (Trail B). A contrast score was again calculated for better estimating the player's cognitive switching ability by subtracting the raw scores of Trail A from the raw score of Trail B (Strauss et al., 2006; Eggermont, Milberg, Lipsitz, Scherder, Leveille, 2009).

Golden's *Stroop test* was used to measure attention control and information processing (Golden, 1975). Participants need to complete three different reading conditions. In each condition, a different reading card is presented: 1.) a card with 100 color words (i.e. 'green', 'yellow', 'red', and 'blue') (psychomotor response), 2.) a card with 100 solid colored rectangles (psychomotor response), and 3.) a card with 100 color words printed in colored ink, yet not the ink of the word itself, in the third condition (inhibition). Participants are asked to read as many colors aloud as possible in 45 seconds in all three conditions. In the third condition the participants need to suppress an automatic response as they were asked to name the color of the ink, instead of reading the word. The numbers of correct responses of each condition were used as raw scores and converted into scaled scores (Rognoni et al., 2013). A scaled value of 10 represents the $50^{th}$ percentile score with 3 points counting as one standard deviation. The error rates per condition were also noted. The number of correct responses in the third condition, divided by the number of correct responses in the second condition, resulted in the Stroop-ratio. This ratio reflects a player's level of inhibition, independently of his / her ability to name colors while avoiding an emphasis on reading ability (Homack & Riccio, 2004; Lansbergen, Kenemans, & van Engeland, 2007). A higher Stroop-ratio indicates better inhibitory control.

**Table tennis performance**

Competition rating scores indicating the player's individual competition performance at the moment of testing were obtained for each player from the Netherlands Table Tennis Association's archives. The higher the rating score the better the player's table tennis performance. The competition rating score compares performances between players (youth and adult players, male and female players) who participate in any of the regional and national competition leagues and does not take into account the classification of the player for para table tennis (Faber et al., 2016). Besides the competition rating score, the classification, the current training hours per week and the total training volume (i.e. accumulation of the training hours per week multiplied by 40 weeks per training year) were acquired by using a short questionnaire to characterize the included players.

*Data collection*

All data were collected between February to June 2016. All players were under similar conditions after a regular training at their training center. None of the players had previous experience with the eye hand coordination test and executive function tests. The eye-hand coordination test was administered first, followed by the D-KEFS Design Fluency test, the Trail Making test and the Stroop test. All measurements were conducted by the same assessor who familiarized herself with the test-protocols and instruction and feedback was given during a training by an expert. The test session lasted for approximately 30 min for each player. The short questionnaire for table tennis parameters was filled in just before or just after the test session.

*Statistical analysis*

IBM SPSS Statistics 23 (IBM Corp., Armonk, New York, United States of America) was used for the statistical analyses. Sample characteristics were presented for the total groups and the subgroups (i.e. elites and non-elites). A Mann-Whitney U test was used to test for differences between the elites and non-elites regarding the sample characteristics competition rating score, the current training hours per week and the total training volume. Spider diagrams were used per classification to demonstrate the players' individual profiles. One-sample Wilcoxon-Signed Rank tests were used to test if the elite and non-elite players scored significantly better or lower than the norm population on the executive function tests. For this purpose, the scaled scores based on the norm values, correcting for age and sex, were used and compared to the median value of the norm population (D-KEFS Design Fluency test 10; Trail Making test 50; Stroop test 10). No comparison could be made to the norm population for the eye-hand coordination test, since no norm values were available in the age-span of the participants for this test. The associations between all test outcomes (i.e. the raw, the scaled / percentile, the contrast as well as the ratio scores) and the table performance outcome (i.e. competition rating score) were firstly evaluated by calculating Spearman's correlation coefficients and partial correlation coefficient with training volume as a controlling variable. Hinkle's rule of thumb was used for the interpretation of the correlation coefficients' sizes (Hinkle, Wiersma, & Jurs, 2003). Secondly, scatter plots were used to explore the players' profiles regarding the level of eye-hand coordination and executive functioning and the level of performance. Only the total score of the D-KEFS Design Fluency test and the outcomes of Trail B of the Trail Making test and color-word condition of the Stroop test were included for this exploration to reflect the executive functioning. Alpha was set at 0.05 for significance for the inferential analyses; the alpha was not adjusted (i.e. lowered) for the multiple testing because of the explorative character of this pilot study. This is supported by Hopkins (2000) stating that the cut-off of 5% can be too stringent for a decision limit in athletes.

## Results

Figure 1 summarizes the raw test scores for each individual player per classification combined with other player characteristics (e.g. sex, age, training volume). The figure holds no diagram for the classification 4 and 6 as no players were included belonging to these sports classes. The rank position shown in figure 1 is the ranking position within the included sample and is based on the competition rating scores. The elite players covered ranking 1 to 8, 10, 13 and 14, the non-elites 9, 11, 12 and 15 to 18. There were five players that had no rating points, which caused the same ranking (Figure 1.d #18). Four players (Figure 1: #3, #6, #9 and #12) had difficulties in catching the ball with both the left and right hand alternately during the eye-hand coordination test. For that reason, they performed the test while only using one hand. Based on the individual profiles in Figure 1, it appears that the elite players tend to catch more balls (eye-hand coordination), to make more unique designs under time pressure and to be faster in making a correct trail (cognitive flexibility), reading words and colours (psychomotor responses) than the non-elites.

No trends were recognized in the exploring subgroup analyses for the players suffering from brain damage.

Table 2 presents the outcomes of the eye-hand coordination and executive function assessment of the elite and non-elite players. There was only one missing value at the Trail Making test, because one player gave up after 180 s. The one-sample Wilcoxon-Signed Rank tests revealed that the elite players scored significantly higher than the median norm values at condition 1 (creativity and working memory) ($p$ = 0.016) and 3 (creativity, working memory and switching ability) ($p$ = 0.033) and at the scaled score of the total of the scaled scores (cognitive flexibility) ($p$ = 0.022) of the D-KEFS Design Fluency test. Still, no significant better scores were found for the Design Fluency test's scaled contrast score reflecting specifically the cognitive switching ability ($p$ = 0.180). The Trail Making test did not reveal any significant differences from the norm median for the elites, but the non-elites performed significantly lower than the 50$^{th}$ percentile on Trail A (psychomotor response) ($p$ = 0.007) and Trail B (cognitive flexibility) ($p$ = 0.002). The non-elites also showed a significantly lower score on the Stroop test than the norm median for the word reading condition (psychomotor response) ($p$ = 0.011). This was not revealed for the other two conditions. In contrast, the elite players performed significantly better at the colour-word condition than the median norm value

(inhibition) ($p$ = 0.016). Only a small number of errors were made in the Stroop test conditions (Figure 1). Nine elites and 7 non-elites showed no errors during the test. Of the remaining players 4 (1 elite and 3 non-elite) had errors (1-3) at the colour-condition and 2 (1 elite and 1 non-elite) had errors (4) at the colour-word condition.

Table 3 shows the evaluation of the associations between the test results and the performance outcome. The eye-hand coordination test showed a significant high positive correlation with the competition rating scores (R = 0.86, $p$ < 0.001) indicating that the better performers of the test are also the better para table tennis players in the regular competition that does not take into account the player's para table tennis classification. Also when controlling for training volume the correlation coefficient remained significant high ($\rho$ = 0.79, $p$ < 0.001). Furthermore, significant low to moderate Spearman correlation coefficients were found between the D-KEFS Design Fluency test outcomes and the competition rating scores (R ranging from 0.49-0.58) and also between the Trail Making test and the competition rating scores (R = -0.71 (Trail A) and -0.46 (Trail B)). The better players tended to perform better on the cognitive flexibility tests. Only the contrast scores of these tests referring to the cognitive switching ability did not reveal any significant association with the table tennis performance outcome. Most of the significant correlations remained moderate when using training volume as a control variable at the D-KEFS conditions; for conditions 2 and 3 and for the total of scaled scores the partial correlations were between 0.46 to 0.57 ($p$ < 0.05). The correlation coefficients in the Trail Making test were somewhat reduced when controlling for training volume in Trail A (raw score $\rho$ = -0.56, $p$ = 0.010; scaled score $\rho$ = 0.49, $p$ = 0.028) but slightly increased in Trail B (raw score $\rho$ = -0.53, $p$ = 0.016). Regarding the Stroop test only the colour condition (psychomotor response) showed a significant moderate positive correlation (R = 0.424, $p$ = 0.049). This correlation became insignificant when controlling for training volume.

Finally, the relations between the level of eye-hand coordination and executive functioning and the level of performance are presented in Figure 2 by means of three scatter plots. No clear trends (e.g. linear or polynomial) could be detected from Figure 2 about the interrelationships of the test outcomes (i.e. eye hand coordination test and executive function tests) and performance. However, as presented in Table 1, a higher rating seems to be accompanied by a higher level of eye hand performance whereas this trend is less clear for the executive function outcomes. Players with a competition rating >1000 points scored ≥ 24 catches/30 seconds in the eye hand coordination task, whereas the players with < 1000 rating points score ≤ 18 catches/30 seconds. In contrast, there was an clear overlap of scores between the players >1000 and <1000 rating scores in the executive functions tests (Figure 2).

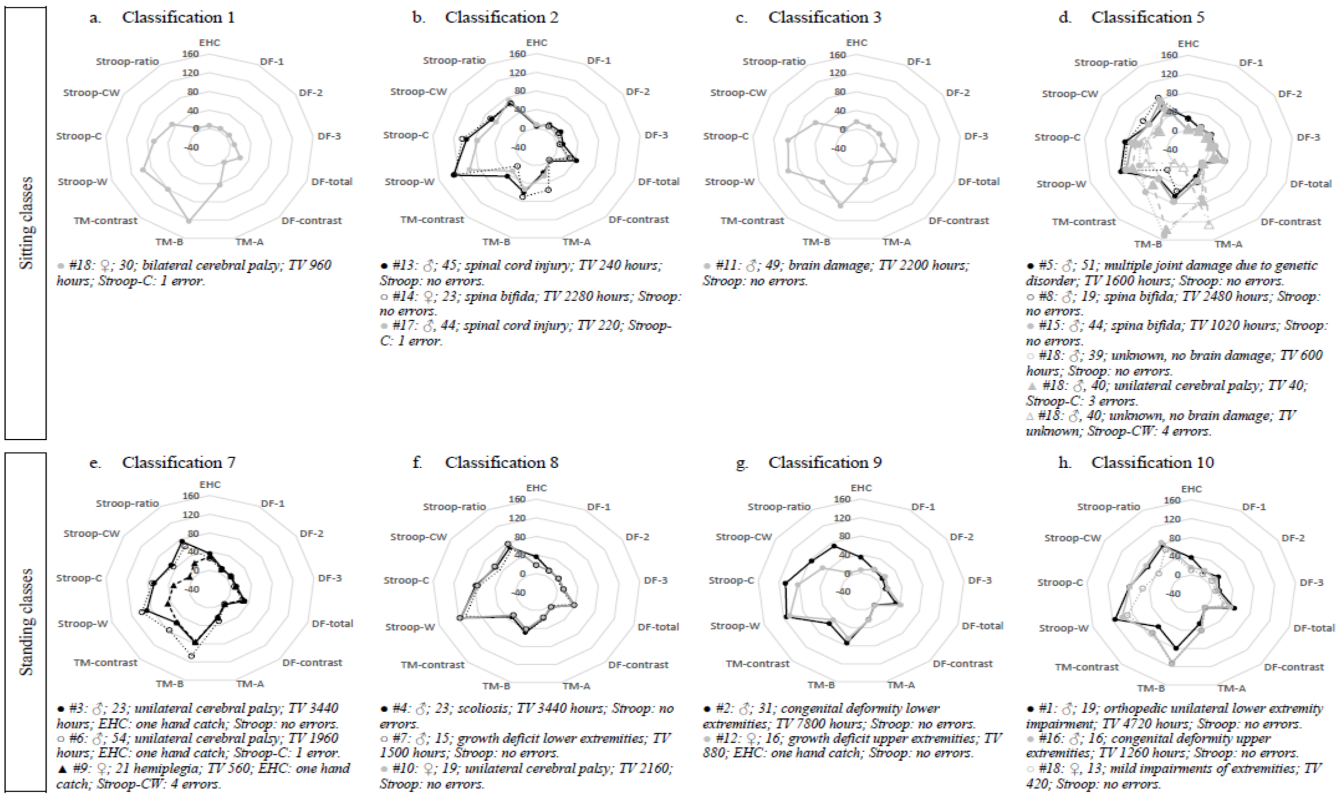


*Figure 1*. Individual profiles of the included players per classification.
Data represent the raw scores per test condition. The results in black refer to the elite players and in grey to the non-elite players. The Stroop-ratio was presented as a percentage. EHC = eye-hand coordination test; DF = D-KEFS Design Fluency test; TM = Trail Making test, Stroop-W = word condition, Stroop-C = colour condition, Stroop-CW = colour-word condition; TV = training volume.

Table 2.
*Eye-hand coordination and executive functions in para table tennis players*

| | | Elite (n=11) | | | Non-elite (n=11) | | |
|---|---|---|---|---|---|---|---|
| | | raw | scaled | *p*-value | raw | scaled | *p*-value |
| Eye-hand coordination (catches/30s)^ | | 26 (4-38) | - | - | 7 (0-30) | - | - |
| D-KEFS Design Fluency test | condition 1 | 13 (7-14) | 13 (8-13)[1] | 0.016* | 9 (3-16) | 9 (4-15) | 0.257 |
| | condition 2 | 10 (7-23) | 9 (7-19) | 0.766 | 9 (1-17) | 9 (2-15) | 0.326 |
| | condition 3 | 10 (5-14) | 12 (7-16)[1] | 0.033* | 8 (2-12) | 10 (4-14) | 0.952 |
| | total of scaled scores | 34 (24-48) | 12 (8-18)[1] | 0.022* | 28 (11-42) | 10 (3-15) | 0.622 |
| | contrast score (3 - (1+2)) | 0 (-2-4) | 10 (8-14) | 0.180 | 2 (-3-4) | 12 (7-14) | 0.165 |
| Trail Making test | Trail A | 22 (16-33) | 60 (10-90) | 0.235 | 41 (22-126) | 10(10-60)[2] | 0.007** |
| | Trail B | 60 (42-107) | 40 (10-70) | 0.088 | 99.5 (64-151)# | 10 (10-20)[2] | 0.002** |
| | contrast score (B-A)^ | 44 (20-77) | -^ | | 60 (15-83)# | - | - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Stroop test | word | 106 (89-130) | 9 (5-14) | 0.181 | 90 (46-128) | 5 (2-14)[2] | 0.011* |
| | color | 78 (67-107) | 10 (8-18) | 0.491 | 67 (30-103) | 8 (2-17) | 0.153 |
| | color-word | 54 (45-76) | 12 (9-17)[1] | 0.016* | 47 (7-67) | 10 (2-15) | 0.310 |
| | ratio (color-word/color)^ | 0.71 (0.62-0.83) | - | | 0.65 (0.23-0.83) | - | - |

Data are presented in medians and ranges. ^Norm values not available. *$p < 0.05$, **$p < 0.05$: showing a significant difference with the norm values. #One missing; the player gave up after 180 s. [1]elite players scored significantly better than the median norm value (D-KEFS Design Fluency test 10; Stroop test 10) ($p < 0.05$). [2]non-elite players scored significantly lower than the median norm value (Trail Making test 50; Stroop test 10) ($p < 0.05$).

Table 3.

*Association between eye-hand coordination and executive functions assessments outcomes and table tennis performance in para table tennis players (n=22)*

| | | Competition rating score versus the raw scores | | | | Competition rating score versus the scaled scores | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | R | $p$ | $\rho$ | $p$ | R | $p$ | $\rho$ | $p$ |
| Eye-hand coordination (catches/30s) | | 0.86** | <0.001 | 0.79** | <0.001 | - | - | - | - |
| D-KEFS Design Fluency test | condition 1 | 0.51* | 0.016 | 0.38 | 0.103 | 0.55** | 0.009 | 0.40 | 0.081 |
| | condition 2 | 0.49* | 0.022 | 0.48* | 0.034 | 0.41 | 0.057 | 0.46* | 0.043 |
| | condition 3 | 0.58** | 0.005 | 0.57* | 0.009 | 0.56** | 0.007 | 0.56* | 0.010 |
| | total of scaled scores | 0.52* | 0.012 | 0.52* | 0.019 | 0.51* | 0.016 | 0.52* | 0.019 |
| | contrast score (3 - (1+2)) | 0.04 | 0.863 | 0.16 | 0.509 | 0.04 | 0.863 | 0.16 | 0.509 |
| Trail Making test | Trail A | -0.71** | <0.001 | -0.56* | 0.010 | 0.66** | <0.001 | 0.49* | 0.028 |
| | Trail B | -0.46*,# | 0.035 | -0.53*,# | 0.016 | 0.20 | 0.375 | 0.286 | 0.221 |
| | contrast score (B-A) | -0.30# | 0.191 | -0.36 | 0.118 | - | - | - | - |
| Stroop test | word | 0.39 | 0.073 | 0.11 | 0.645 | 0.41 | 0.056 | 0.21 | 0.373 |
| | color | 0.42* | 0.049 | -0.07 | 0.773 | 0.44* | 0.040 | -0.02 | 0.929 |
| | color-word | 0.35 | 0.107 | -0.09 | 0.715 | 0.36 | 0.105 | -0.02 | 0.937 |
| | ratio (color-word/color) | 0.23 | 0.307 | -0.14 | 0.550 | - | - | -- | |

R = Spearman's correlation coefficients. $\rho$ = partial Spearman's correlation coefficients correcting for training volume. *$p < 0.05$ and **$p < 0.01$ showing a significant difference between the groups. #one missing; the player gave up after 180 s.

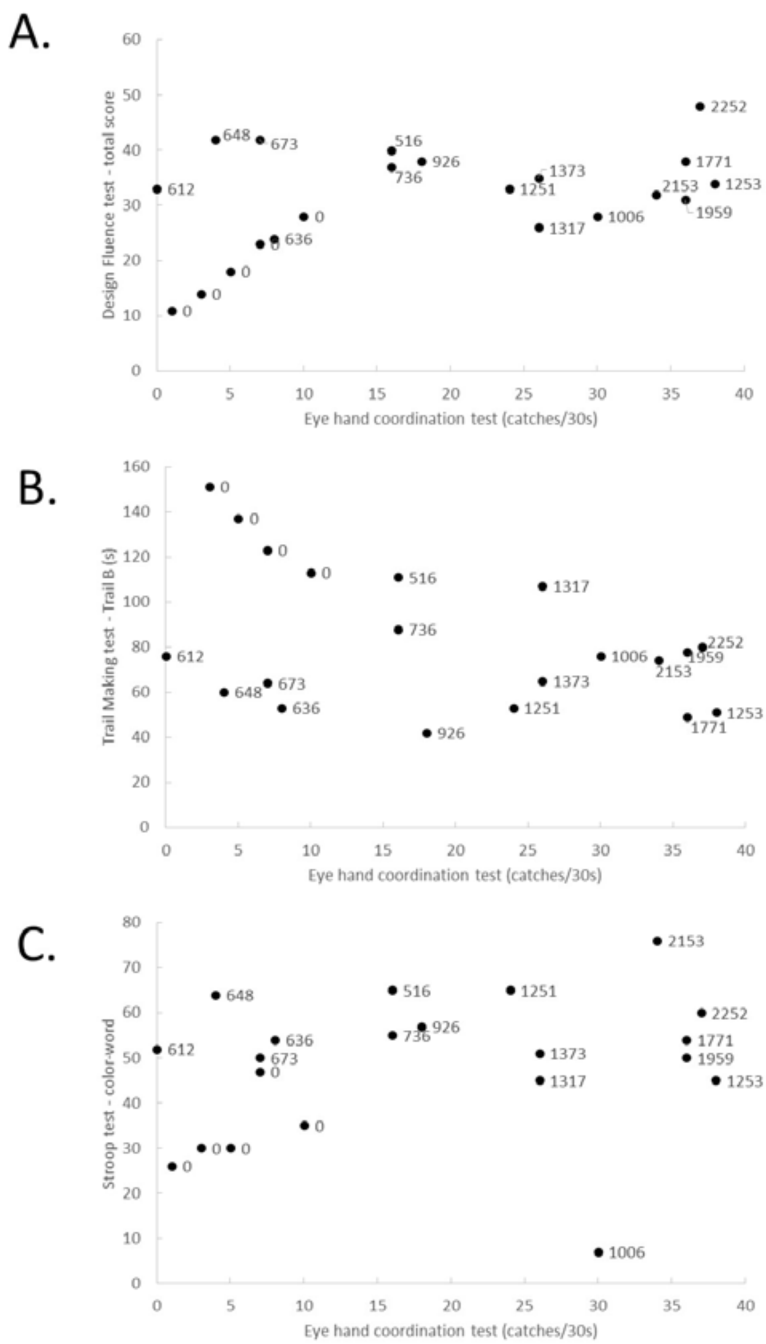


*Figure 2.* Exploration of the association between the level of eye-hand coordination and executive functioning and the level of performance.

## Discussion

The results of this pilot-study indicate that, as hypothesized, the current level of table tennis performance in para table tennis players is related to the player's level of eye-hand coordination and the measured executive functions even when there is control for the training volume. The results concerning eye-hand coordination correspond to the findings in typical developing racket sport players (Faber et al., 2014, 2016; Mantis et al., 1998; Nikolić et al., 2014; Filipčič & Filipčič, 2005; Filipčič et al., 2010; Panjan et al., 2010). Eight of the elite para table tennis players scored within the range (mean ± 2 *SD) presented by the typical developing Dutch elite and sub-elite table tennis players (elite 33 ± 5; sub-elite 30 ± 5) (Elferink-Gemser et al., 2018), whereas only one non-elite para table tennis player reached this level. As eye-hand coordination might differ considerably in para table tennis players as a consequence of the various impairments, this might even be more related to the playing level than in typical developing players. Especially in those players where the coordination of the hand function is impaired as a consequence of a neurological condition (e.g. brain damage). On the other hand, it is important to keep in mind that the analysis was conducted on players competing in different playing classes. A within-class analyses is necessary to gain more insight in the association of the eye hand coordination test outcomes and the level of performance. Especially as the game characteristics between classes can vary (Fuchs et al., 2019).

Regarding the executive function results, it seems likely that specifically cognitive flexibility and information processing are related to performance in para table tennis players. The elite players showed better levels of creativity and working memory compared to the norm population (corrected for age and sex) whereas the non-elite players did not, which was associated with a higher performance level in national competition even when controlling for training volume. These findings are in line with the results of previous studies conforming the association between cognitive flexibility and sports performance (Huijgen et al., 2015, Verburgh et al., 2014; Vestberg et al.,2012). Moreover, recently published data in typical developing elite and sub-elite Dutch table tennis players also revealed that these high-level players score significantly better than the norms on creativity and working memory ($p < 0.05$) (Elferink-Gemser et al., 2018). In contrast, Huijgen et al. (2015) did not find differences in the lower cognitive functions, i.e. information processing, between elite and sub-elite youth soccer players. Our results showed that the non-elite players' psychomotor responses were slower than those of the norm population and of the elite players and that these were associated with a low competition level. This is possibly best explained by the differences in the included sample and perhaps in the difference of game speed between soccer and table tennis. Yet, it must be acknowledged that although contrast scores were used to better indicate the level of specific cognitive functions, the influence of motor speed on the results has not been evaluated by means of a pure motor speed task. Including an appropriate test for the para table tennis players in future studies measuring this construct (e.g. finger tapping task) might provide new insights. For the executive function tests, it is also important to conduct within class analyses with specific characteristics (Fuchs et al., 2019) to better understand the value for para players competing in the same class.

Although, these interpretations of the results seem logical and supported by other studies, hard conclusions based on our results cannot be drawn. However, this study is intended to serve as a starting-point and some concessions for feasibility reasons had to be made in the study design and the analyses. First, this study used a cross-sectional design due to time-constraints, which prevents any conclusion about causality. Although associations were found, it cannot be confirmed whether better performance was a consequence of better eye-hand coordination or executive functioning. Longitudinal studies are needed in the future. Second, no hard conclusion can be drawn about the heredity component (i.e. natural ability) or trainability of eye-hand coordination and the measured executive functions to influence the performance level. A better insight in the influence of training on the outcome variables is needed. Although statistical corrections were made for the players' total training volume and it was shown that most associations remained significant which could refer to a natural ability, it must be acknowledged that the design is cross-sectional and the sample of this study is only small. Both prevent us to make conclusions about the direction of the associations that was found. Third, the reproducibility of the eye-hand coordination test has not been studied yet in a sample including para table tennis players and using the modification for players with a unilateral impairment of the upper extremity (i.e. using only one hand). However, since the reproducibility was already confirmed satisfactory in young children (age 6-10) (Faber et al., 2015), we assume that this is generalizable for our sample. Fourth, general tests were used to assess the executive functions. Concerning task-specificity future studies could focus on (the development of) tests that are more closely connected to table tennis. Fifth, the type-1 error is increased in this study; the alpha was not adjusted for multiple testing as we intended to find first starting points. It is recommended, however, to take the possibility of adjustment of the alpha into account in future studies (Field, 2013). Finally, the small sample size prevented subgroup analyses per age and classification. Such analyses are crucial to better understand what key factors determine performance in a certain age and specific class in para table tennis. An international approach in which data of the nation's samples can be combined and analyzed together is recommended for this purpose.

## Conclusions

In conclusion, this pilot-study intends to serve as a starting-point for searching determinants of performance in para table tennis players. Although there are limitations in this study and no hard conclusion can be drawn, the results present a first profile of para table tennis players regarding their eye-hand coordination and executive functions and the relationship of these constructs with the performance level. We call scientists, associations and coaches to start an international cooperation in this field to make it possible to evaluate determinants for performance per classification and per age-group including eye-hand coordination and executive functions. Moreover, we recommend a longitudinal approach in which players will be monitored over time.

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# Do left-handed players have a strategic advantage in table tennis?

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## Abstract

The reasons for the overrepresentation of left-handed players (LHps) in some sports are widely discussed in the literature. In light of this debate, this study aimed to assess the associations between players' handedness and selected performance indicators in table tennis, where LHps represent 25% of top-level players. A notational analysis was conducted on 20 men's matches including any combination of players' handedness. Participants were in the first 150 positions of the ITTF world ranking at the moment the matches were played. The table area of ball bouncing after serving, and the shot type used by the receiving and subsequently the serving player, were recorded for 1515 rallies. Each half of the table was divided into six equal rectangular areas. There was a significant effect of players' handedness on percentage of ball bouncing in different areas. Specifically, LHps showed a greater capacity (or choice) to adjust the serve (in terms of areas of ball bouncing) than right-handed players (RHps) according to the opponent's handedness. Furthermore, LHps used offensive shots more frequently. In conclusion, both play strategy and characteristics such as higher offensiveness, together may contribute to the success of LHps in table tennis. These findings emphasise the need for a multifactorial approach in future research aiming to understand why LHps may be advantaged in different sports.

Keywords: *Racket sports; Table tennis; Notational analysis; Handedness; Serve-return strategy*

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## Introduction

In many sports, and especially in those disciplines where the actions of players may directly affect the actions of their opponents (i.e., interactive sports), left-handed players (LHps) are overrepresented by up to 30 % of competitors (Loffing, Hagemann, & Strauss, 2009), leading to the supposition that left-handedness may be beneficial for achieving high competitive performance (Llaurens, Raymond, & Faurie, 2009). An innate superiority linked to better neuropsychological predispositions (Bisiacchi, Ripoll, Stein, Simonet, & Azemar, 1985; Dane & Erzurumluoglu, 2003; Judge & Stirling, 2003), and a negative frequency-dependent strategic advantage (Brooks, Bussiére, Jennions, & Hunt, 2003; Raymond, Pontier, Dufour, & Moller, 1996; Schorer, Loffing, Hagemann, & Baker, 2012) are two well-known explanations of how LHps may be advantaged over right-handed (RH) players. Possible mechanisms contributing to an advantage for LHps were also postulated by researchers, who identified advantages linked to perceptual-cognitive skills (Loffing, Hagemann, Schorer, & Baker, 2015) or to biomechanical factors (Solomito, Ferreir, & Nissen, 2017).

The factors leading to the overrepresentation of LHps have been assessed in several interactive sports, including team sports such as basketball and soccer, and individual sports such as fencing, boxing and racket sports. In particular, previous findings in the tennis research area supports the view that LH tennis players have advantages of tactical or strategic nature (Hagemann, 2009; Loffing, Hagemann, & Strauss, 2010). Indeed, many players are typically less accustomed to play against LHps than right-handed (RH) players, and might be not well prepared to counter effectively the shots made by these opponents. However, more recently, it was shown that LHps are overrepresented at amateur level but no more so among top-level players (Loffing, Hagemann, & Strauss, 2012). A possible explanation is that professional players carefully analyze the matches played in the major tournaments and have a wide knowledge of their opponents' playing strategies. Therefore, at the highest competitive levels, left-handedness would seem to represent no more of an advantage for competitive performance.

Contrary to tennis, a high representation of LHps can still be observed among top-level table tennis players. Indeed, LHps represented 25 % of the top 100 male players in the world ranking at Oct 2015 (data taken from the International Table Tennis Federation website, www.ittf.com). Since it is likely that the world's best table tennis players study their opponents with no less professionalism than tennis playing counterparts, LHps may have competitive advantages that cannot be nullified by the players' preparation.

The serve plays an important role for performance in racket sports (Aviles, Navia, Ruiz & Martinez de Quel, 2019; Cui, Gómez, Gonçalves & Sampaio, 2018; Katsikadelis, Pilianidis, & Mantzouranis, 2013; Ma, Liu, Tan, & Ma, 2013), and is certainly an aspect that may provide a key to understand how LHps are advantaged in table tennis. Loffing et al. (2009) assessed whether LHps could have an advantage related to the serve in professional tennis players. Those authors showed that the zone of the opponent's pitch in which the ball was sent, and the angle of lateral ball flight, was different between RHps and LHps, forcing the opponent to consider a different direction of the serve and to adjust the return stroke due to the different spin imposed on the ball. This finding led the authors to conclude that the serve is particularly relevant for the determination of a possible advantage of LHps over RH opponents. To our knowledge, no study has assessed the relationships between handedness and the serve bouncing/landing area in table tennis. In table tennis matches, the service imposes greater pressure on the receiver, creating favourable striking conditions for the next shot (Zhang, Liu, Hu, & Liu, 2014). Moreover, the effectiveness of the serve and of the immediately subsequent shots has a great impact on the outcome of a rally in table tennis (Zhang et al., 2014). It may be thus hypothesised that, also in table tennis, the advantage of LHps may derive from characteristics of the serve and, consequently, from aspects related to the first shots of the rally.

In the recent years, scientific research has applied match and notational analysis to the most popular racket sports: badminton (Abdullahi & Coetzee, 2017), tennis (Cui et al., 2018), and table tennis (Malagoli Lanzoni, Di Michele & Merni, 2014; Fuchs et al., 2018). Using such an approach, this study aimed to assess the associations between the players' handedness and selected characteristics of the serve and the first two shots of the rally in top-150 table tennis matches.

## Methods

### *Data collection*

A total of 20 men's table tennis matches, played by 40 players (19 Europeans and 21 Asians) were examined. All players adopted an offensive playing style because they were not using a backhand chop stroke when playing far from the table and they did not use long-pimple rubbers, the typical rubbers used by defenders. The mean (±SD) age, height and mass of the players were 26.3 (±5.3) years, 178.7 (±5.9) cm, and 70.7 (±6.0) kg respectively (data taken from www.ittf.com). The matches sampled was based on a random selection of matches played between 2008 and 2014 by the top 150 players in the world in international events (Olympic Games, Individual and Team World Championship, World Cup, Pro Tour circuit, and ITTF world team classic). This kind of selection was done to include only one game for each player. All the matches were recorded from broadcasts of a free online TV channel, who agreed to the use of the video recordings for conducting the present study. The study was deemed exempt from ethical approval by the University of Bologna Bioethics Committee.

The handedness of players was established according to which hand was used to hold the racket (Peters & Murphy, 1992). RHps (n = 20) and LHps (n = 20) were equally represented. Furthermore, 5 of the examined matches were played between two RHps, 5 between two LHps, and 10 between a RHp and a LHp. The matches were played to the best of five sets, finishing 3-2 (n = 4), 3-1 (n = 2), and 3-0 (n = 1), or to the best of seven sets, finishing 4-3 (n = 2), 4-2 (n = 2), 4-1 (n = 7), and 4-0 (n = 2).

A table tennis coach with international coaching experience collected the examined indicators on a spreadsheet while watching the video of matches in slow motion with the software Kinovea (www.kinovea.org). The following indicators were recorded for each rally:

- Area of the table where the ball bounced after the player's serve (abbreviated as "Area"). According to a previous study (Malagoli Lanzoni et al., 2014), each half of the table was divided in six equal rectangular areas (see Figure 1). Three areas are in the front (closer to the net) part of the table, respectively numbered as 2 (front right), 3 (front center), and 4 (front left), and three areas are in the rear (closer to the player) part of the table, respectively numbered as 1 (rear right), 6 (rear center), and 5 (rear left)
- Type of shot used to hit the ball by a player when receiving the serve (defined as "S2", according to Zhang et al., 2013). Three shot types were considered according with literature (Malagoli et al., 2014): flick (attacking shot typically executed when the ball has bounced closed to the net), push (a neutral shot imparting a back-spin effect to the ball), and top (an attacking shot imparting a top-spin effect to the ball). These shot categories included the great majority of S2 shots. Rallies with a different S2 shot type, or rallies ended immediately after the serve without a response of the receiving player, were discarded from subsequent analyses.
- Type of shot used to hit the ball by the serving player when receiving the S2 shot (defined as "S3" according to Zhang, et al., 2014). Five shot types were considered: flick, push, top, block (a defensive shot performed in response to a top), and top counter top (a top, i.e. an offensive shot, performed against a top).

### *Reliability*

For one randomly selected match, data of serve bouncing area, shots types used to return the service and to hit the subsequent ball were recorded by three national table tennis coaches. Furthermore, one of the coaches recorded the same match three times. Krippendorff's alpha (ranging between -1 and 1, where 1 indicates perfect agreement) was calculated to assess inter-and intra-operator reliability (Krippendorff, 2004). For the serve bouncing area and shot type, the inter-observer reliability alpha was equal to 0.94 and

0.89 respectively and concerning the intra-observer reliability it was equal to 0.99 and 0.99 respectively.

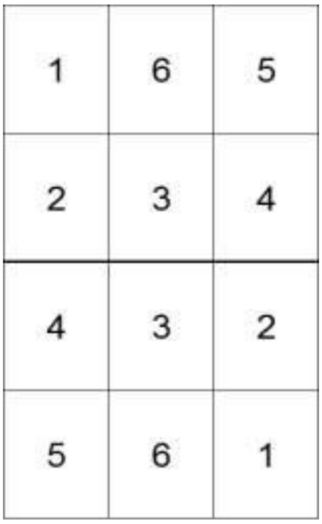


*Figure 1*. Six-area subdivision of the table. The thick line represents the net.

### *Statistical Analysis*

All data are presented as the mean and standard deviations. For any player (n=40), individual percentages of area of ball bouncing, S2 shot type and S3 shot type were calculated and used as the dependent variables. Six one-way ANOVAs with Tukey's post-hoc comparisons were used to assess the effect of players' handedness (PH) on the mean percentages of areas of ball bouncing. Four PH categories were used in these analyses: both RHps (RR), both LHps (LL), different-handed opponents with the RHp serving and the LHp receiving (RL), different-handed opponents with LHp serving and the RHp receiving (LR). Furthermore, two-way ANOVAs were used to assess the effects of the serving player handedness, opponent handedness, and their interaction, on the mean percentages of S2 (three ANOVAs) and S3 (five ANOVAs) shot types. In all ANOVAs, partial eta squared (#2) were used as the effect size. The statistical analysis was carried out with the software R, version 3.2.3 (R Core Team, 2011). For all the analyses, the statistical significance was set at $p<0.05$. For all the analyses (that is, those concerning the area of ball bouncing, the S2 shot type, and the S3 shot type), the alpha level was corrected dividing it by the number of statistical tests performed in that analysis.

## Results

A total of 1515 rallies was examined for this analysis, with an average of 38 rallies per player. In each of the rallies, RHps executed the serve while standing close to area 5 (rear/left) of their own table side, whereas LHps executed the serve while standing close to area 1 (rear/right). The overall frequency distributions for, PH, Area, S2, and S3, were, respectively, as follows:

- PH: RR: 344 (22.7 %), RL: 397 (26.2 %), LR: 412 (27.2 %), LL: 362 (23.9 %);
- Areas: 1: 93 (6.1 %), 2: 199 (13.1 %), 3: 904 (59.7 %), 4: 204 (13.5 %), 5: 85 (5.6 %),
  6: 30 (2.0 %);
- S2: flick: 300 (19.8 %), push: 968 (63.9 %), top: 247 (16.3 %);
- S3: block, 165 (10.9 %); flick, 141 (9.3 %); push, 295 (19.5 %); top, 794 (52.4 %);
  top counter top, 120 (7.9 %).

Figure 2 shows the mean percentage values of area of ball bouncing for any players' handedness combination. For area 1, there was an effect of PH ($F_{3,36}=7.96$, $p<.01$, $\eta^2=0.40$). Specifically, when both the players were left-handed, there was a higher percentage of balls sent into area 1 than in any other PH category. A significant effect for PH was also observed for area 2 ($F_{3,36}=5.36$, $p<.01$, $\eta^2=0.31$), with the condition of both right-handed players showing higher percentages of ball bouncing in area 2 than the conditions of both left-handed players and of right-handed serving players and left-handed receiving player. No effect of PH on mean percentage of ball bouncing was observed for areas 3 ($F_{3,36}=1.83$, $p=.16$), and 4 ($F_{3,36}=2.12$, $p=.11$). For area 5, there was a significant effect of PH on percentage on ball bouncing in that area ($F_{3,36}=4.43$, $p<.01$, $\eta^2=0.27$). Specifically, the post-hoc comparisons revealed a higher percentage in the condition of both right-handed players than in the condition of both left-handed players. Finally, no effect of PH on mean percentage of ball bouncing was observed for area 6 (F3,36=0.54, p=.66).

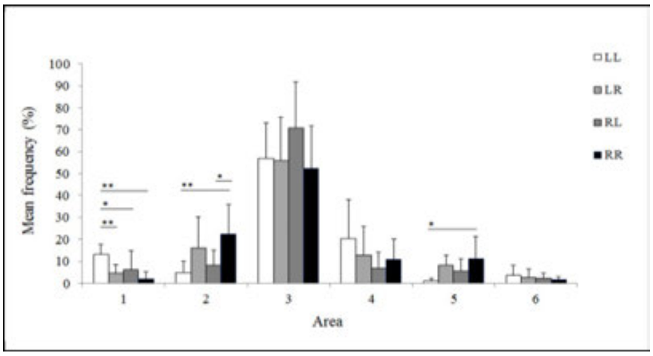

*Figure* 2. Mean and standard deviations (represented by vertical bars) frequencies for area of ball bouncing in the four examined handedness combinations.

LL = both LHp serving and receiving; LR = LHp serving and RHp receiving; RL= RHp serving and LHp receiving; RR = both RHp serving and receiving;

* = p<0.05; ** = p<0.01

Tables 1 and 2 display the mean percentages of shot distribution for any combination of serving player's handedness and receiving player's handedness, for S2 and S3, respectively. For all S2 shot types, there was no significant effect of serving player's handedness, receiving player's handedness, and their interaction (all p >0.05). Similarly, no significant effect (p>0.05) was observed of serving and receiving player's handedness for S3 block, flick, top, and top counter top, nor for the main effect of serving player's handedness for the top ($F_{1,36}$=3.544, p=0.07, η2=0.09), with left-handed players showing a higher mean percentage than right-handed players. Finally, for S3 push, there was a significant main effect of serving player's handedness ($F_{1,36}$=5.248, p=0.03, η2 =0.13), with right-handed players showing a higher mean percentage of push shots than their left-handed counterparts.

Table 1.

*Type of shot distribution of S2 in relation to serving and receiving player's handednes.*

| Players' handedness | Shot type (mean % ± SD) | | |
|---|---|---|---|
| | Flick | Push | Top |
| LL | 22.7 (14.8) | 58.2 (15.4) | 19.1 (7.7) |
| LR | 18.2 (13.8) | 59.5 (14.6) | 22.2 (6.8) |
| RL | 18.8 (6.7) | 62.4 (19.0) | 18.8 (13.9) |
| RR | 25.4 (16.3) | 61.3 (17.8) | 13.3 (11.9) |

LL = both LHp serving and receiving; LR = LHp serving and RHp receiving; RL = RHp serving and LHp receiving; RR = both RHp serving and receiving

Table 2.

*Type of shot distribution of S3 in relation to serving and receiving player's handedness.*

| Player handedness | Shot type (mean % ±SD) | | | | |
|---|---|---|---|---|---|
| | Flick | Push | Top | Block | Top c top |
| LL | 9.2 (6.7) | 15.8 (9.2) | 56.9 (9.1) | 12.3 (5.2) | 5.7 (3.3) |
| LR | 7.1 (5.4) | 16.8 (12.4) | 55.1 (13.2) | 12.3 (6.5) | 8.6 (6.2) |
| RL | 9.7 (8.3) | 23.3 (11.1) | 47.8 (12.4) | 10.4 (11.2) | 8.7 (10.7) |
| RR | 11.7 (11.0) | 23.9 (7.2) | 49.9 (13.0) | 8.2 (7.5) | 6.3 (5.8) |

Top c top = top counter top.

LL = both LHp serving and receiving; LR = LHp serving and RHp receiving; RL = RHp serving and LHp receiving; RR = both RHp serving and receiving

## Discussion and conclusions

Previous studies suggest that left-handedness may be beneficial for achieving higher competitive performance (Llaurens et al., 2009) or enhances probability of success in interactive sports (Schorer et al., 2012). Therefore, the over representation of left-handed athletes reflects their performance advantages in interactive sports (Loffing et al., 2015).

This study aimed to assess the associations between players' handedness and selected performance indicators in table tennis, where LHps represent 25% of top-level players.

In the present study, we assessed some aspects of the play strategy at the start of rallies in top 150 table tennis matches characterized by any different combinations of players' handedness. Notational analysis was chosen as the approach for data collection, since this method turned out to be effective to assess technical/tactical parameters in many sports including, first and foremost, racket sports (Abdullahi & Coetzee, 2017; Fuchs et al., 2018; Hughes, 1998; Lees, 2003; Malagoli Lanzoni et al., 2014). The results showed an effect of players' handedness on area of ball bouncing and S3 shot type, suggesting that handedness can affect the play strategy.

The analysis of the effect of PH on mean percentage of ball bouncing in each area of the table (see Figure 2) provides a key to understanding whether and how left-handed players can benefit of strategic advantages at the very start of rallies. This advantage could be linked to the possibility of playing high effective offensive shots such as top spin (Malagoli Lanzoni, Bartolomei, Di Michele, & Fantozzi 2018), after the serve, by serving players. When both the players were RH, a higher percentage of balls were sent towards areas 2 (close to the net on the forehand side) and 5 (close to the receiving player on the backhand side) than when both players were LL. Probably, forcing the opponent to stretch out and respond with a forehand was a deliberate strategy chosen by some players with the aim to make the opponent more vulnerable to a subsequent attack on the backhand corner. On the contrary, according to the above considerations, it's unlikely that any of the players aimed to send, intentionally, the ball towards area 5. Therefore, in matches between two RHps, most balls having reached area 5 were likely directed towards area 3 by the serving player, instead. Arguably, these balls bounced on area 5 (probably quite close to the centre of the table, i.e. at the boundary between areas 3 and 5), as a consequence of the sidespin effect of the ball and then to its trajectory. In other words, due to the side spin, the ball trajectory goes automatically toward backhand side, from area 3 to area 5. A serve of this kind (known as forehand pendulum), interestingly, results in being not very easy to attack for the receiving player, despite the ball not bouncing close to the net. Indeed, differently from what would happen if the ball arrived in areas 1 and 6, the receiver has to attack with a backhand top, a shot generally more difficult to execute than a forehand top. Moreover, in these serves, the ball tends to bounce for a second time near the table edge, resulting in increased hitting difficulty for the receiving player. Literature confirms that forehand top spin is the most used stroke used by top-level table tennis players (19.5%) compared to top backhand (13.5%), and it was more associated with winning outcomes (Malagoli Lanzoni et al., 2014).

When considering the matches between two LHp, given that the backhand and forehand sides are inverted for a LH receiver, the observed area pattern was consistent to that of matches between two RHp, with a higher percentage of balls reaching area 1 than in matches between two RHp, presumably for reasons similar to those noted above. Conversely, dissimilar patterns were observed between the two cases regarding different-handed players. On the one hand, when LHps served against RHps, the mean percentage of ball bouncing was almost similar to that of matches between two RHps, revealing no significant differences between LR and RR for any of the six examined areas (see Figure 2). On the other hand, when RHps served against LHps, the mean percentage of ball bouncing showed some differences when compared to that of LHps serving against LHps. In particular, when examining area 1, a lower percentage of balls were sent to that area (close to the player on the backhand side) in the RL than in the LL condition. These results would seem to indicate that, to some extent, LHps are more capable than RHps to adjust their serving strategy to the opponent's handedness. At this playing level, it's reasonable to expect that any player knows very well what would be the optimal way to serve against any opponent, as in tennis (Loffing et al., 2009). Therefore, it is not straightforward to understand why RHps seem not to adapt their serving strategy, at least for what concerns the area of ball bouncing, when facing LHps opponents. Probably, many RHps believe a good solution is using in any case the serving technique they habitually train and master the best (the one optimal against RHps), despite the increased risk to be immediately attacked if the opponent is a LHp. In other words, these players do not consider it necessary to switch to a technique they are less confident with, only for the purpose to address the ball towards "less dangerous" areas. Irrespective of its reasons, the capacity (or choice) to adjust the serve (in terms of areas of ball bouncing) to the opponent's handedness, observed in LHp but not in RHp, may be regarded as a possible factor contributing to the success of LHp in top-level competitive table tennis.

An important effect of handedness was observed on the S3 shot type, even though there was not a main effect of serving player's handedness as revealed by two-way ANOVAs. In particular, irrespective of the opponent's handedness, left-handed players showed a lower percentage of push shots and a trend to a higher percentage of top shots as compared to right-handed players (Table 2). Since performing a top or a push can be considered, respectively, a more offensive or a more defensive approach to a similar situation faced by a player, these findings suggest that in this kind of match the LHp tend to generally adopt a more offensive strategy compared to RHp. This kind of behavior may be related to a possible higher aggressiveness of LHps, supposed to be a factor contributing to their success in competitive sport (Dane & Sekertekin, 2005).

In summary, the present results show that the start of rallies in table tennis is influenced by the handedness of the two players. These findings, although limited to the set of selected indicators, provide clear information to explain how LHps may be advantaged in top-level table tennis. Our hypothesis that, under some aspects, the advantage of LHps could derive from serve characteristics, was supported by the results. Although limited to the area of ball bouncing as a descriptor of the serve effectiveness, it seems that LHps are more capable than RHps to optimally adapt the serving strategy to the opponent's handedness. This result corroborates a possible strategic advantage of LHps. Nevertheless, the analysis of the shot type at S2, and especially at S3, shows that RHps tend to make conservative choices, even if not forced to do so, while LHps tend to opt for more offensive choices. As in other sports, an innate higher aggressiveness of LHps may be a likely explanation for this kind of choice (Dane & Sekertekin 2005). It may be concluded, therefore, that the advantage of left-handed players in top-level table tennis may have a multifactorial origin, showing links with both play strategy aspects and possibly innate characteristics such as aggressiveness.

Some limitations of the present study should be acknowledged. In particular, future perspectives should include the analysis of differences between male and female players, and between players of different performance levels (top-class, high-level, advanced, intermediate, beginner, etc.). Furthermore, the outcome of rallies may also be examined in relationship with other performance variables.

From a practical point of view, the present results suggest the need to improve technical-tactical skills through specific training and more attention needs to be given to the systematic introduction of specific exercises for the different handedness.

In conclusion, the present study showed that, in top-150 table tennis players, the play strategy is influenced by the handedness of players. Indeed, left-handed players were more able than right-handed players to adapt the serving strategy to the opponent's handedness. Furthermore, left-handed players showed a more offensive play strategy. Therefore, the advantage of left-handed players in top-level table tennis may derive from both play strategy aspects and characteristics as higher aggressiveness. These findings add new insights to the debate on why left-handed players may be advantaged over right-handed players in interactive sports.

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