Correlations between the equine metacarpophalangeal joint angulation and toe conformation in statics

Jenny Hagen¹*, Kaid Kojah¹ and Michael Geiger²

¹Institute of Veterinary Anatomy, Histology and Embryology, Faculty of Veterinary Medicine, Leipzig University, Germany
²University Hospital for Horses, Faculty of Veterinary Medicine, Leipzig University, Germany

Abstract
The angulation of the equine fetlock determines the load of associated tendons and probably their predisposition for injuries. However, it is questionable how the individual toe conformation and tendon properties interact with the dorsal metacarpophalangeal joint angle (DMPJ). Data are needed for a tangible evaluation of the equine limb conformation for more specific orthopaedic treatment. The aim was to evaluate the correlation between the DMPJ, toe conformation and cross-sectional area (CSA) of both flexor tendons; the superficial digital flexor tendon (SDFT) and deep digital flexor tendon (DDFT). Thirty Warmblood horses were available for the study. Lateromedial radiographs of the toe and fetlock and transverse ultrasound images of both flexor tendons were obtained from three zones. The DMPJ, length and angle of the phalanges and CSA SDFT/DDFT were measured. In addition, hoof angle, wither height, age, and sex were documented. Correlations were calculated using Pearson’s test. A paired t-test was used to evaluate left–right differences. Length and angle of the proximal and middle phalanx were significantly associated with the DMPJ (r = -0.28 – -0.45, p<0.001-0.04). Neither the angle of the hoof and distal phalanx nor the CSA SDFT/DDFT, showed a noticeable correlation with the DMPJ. Significant left–right differences occurred for the DMPJ (p<0.002) and the angle of the proximal and middle phalanx (p<0.01 – 0.002). A moderate negative correlation was shown between the DMPJ and wither height (r = - 0.31, p=0.04). Results represent only a specific population. The study provides only a static evaluation of a dynamic situation. In a clinical context, it might be useful to focus on the angulation and length of the pastern to evaluate the individual load affecting the DMPJ and its associated structures. These findings might be relevant for orthopaedic treatments and shoeing recommendations.

Keywords: Fetlock, Flexor tendons, Horse, Joint angle, Toe conformation.

Introduction
The incidence of disorders affecting the metacarpophalangeal joint (MPJ) and its associated structures is reported to be high in equine athletes (Dyson, 2002; Murray et al., 2010). Therefore, the equine fetlock is of significant interest in diagnostics and treatment (Floyd and Mansmann, 2007; Ross and Dyson, 2011).

In particular, the sagittal angulation of the MPJ determines the load on associated tendons and ligaments and their susceptibility to injuries (Rooney, 1984; Weller et al., 2006; Lawson et al., 2007). The equine fetlock provides dynamic stability due to its complex architecture and strongly extended orientation (Clayton et al., 1998; Hodson et al., 2000; Dyce et al., 2010).

The equine limb acts as a mass-spring system due to the extension of the MPJ and the elastic recoil in long tendons of the distal limb (Clayton et al., 1998; McGuigan and Wilson, 2003; Patel, 2010). In particular, the superficial digital flexor tendon (SDFT) is specialised for enhanced elastic energy storage (Biewener, 1998; McNeill Alexander, 2002; Dowling and Dart, 2005). Additionally, both flexor tendons and further associated structures are arranged and interact as suspensory apparatus of the MPJ. These structures support the MPJ in resisting hyperextension during load (Dyce et al., 2010). High load causes a high incidence of pathologies in these structures (Dyson, 2002; Murray et al., 2010), as is frequently seen in the SDFT and DDFT (Doming et al., 2000; Patterson-Kane and Firth, 2009).

The dorsal metacarpophalangeal joint angle (DMPJ) determines the degree of extension in the fetlock. It is reported to be one evaluable parameter that can be used to estimate the load affecting the MPJ and the flexor tendons (Herbst, 1985; Anderson et al., 2004). Corrective shoeing is frequently used to influence the hoof angulation with the intention to change the DMPJ to relieve associated structures, such as the SDFT or DDFT (Crevier-Denoix et al., 2001; Denoix et al., 2007; Lawson et al., 2007). The individual DMPJ seems to be influenced by further factors (Hüppler et al., 2016; Hagen et al., 2017).

*Corresponding Author: Dr. Jenny Hagen. Institute of Veterinary Anatomy, Histology and Embryology, Faculty of Veterinary Medicine, Leipzig University, An den Tierkliniken 43, 04103 Leipzig, Germany. Email: hagen@vetmed.uni-leipzig.de
The aim of the present study was to examine how the individual toe conformation and the dimensions of supporting structures, such as the cross-sectional area (CSA) of both flexor tendons, are associated with the DMPJ. These objective data shall provide a base for a tangible evaluation of the equine limb conformation as a basis for more specific orthopaedic treatment, trimming or shoeing (Deniox et al., 2007; Floyd and Mansmann, 2007). Therefore, this study examined the correlation between the individual toe conformation, the CSA SDFT/DDFT, and the DMPJ based on the following hypotheses:

1. No significant left–right differences in the DMPJ occur in the forelimbs of an individual horse.
2. The steeper the dorsal wall angle of the hoof (DWA) or the angle of the distal phalanx in relation to the ground (APIII), the lower the DMPJ.
3. The longer length of the proximal phalanx (LenPI), length of the middle phalanx (LenPII) and lower angle of the proximal phalanx in relation to the ground (APII), angle of the middle phalanx in relation to the ground (API) the proximal and middle phalanx, the lower the DMPJ.
4. The larger the CSA SDFT/DDFT, the lower the DMPJ.
5. Wither height is correlated with the DMPJ, whereas sex and age do not interact with this parameter.

**Materials and Methods**

**Animals**
A cohort of 30 clinically sound Warmblood horses without any history of orthopaedic disorders was selected from a larger population (n = 110) of horses resident in two riding stables. The horses showed the following signalment: mean wither height measured at the fifth thoracic vertebra 155.24 cm (145–172 cm), mean age 12.24 years (4–25 years), 15 geldings, 15 mares; breeds: 13 German Warmbloods, 2 Oldenburger, 5 Pura Raza Espanola, 10 Warmblood crossbreed. All animals were kept, fed, managed, and used under similar conditions. In both stables all the horses experienced 8–14 hours of exercise per week. No high performance horses used for a specific discipline were included in this study. All horses were barefoot and trimmed regularly. Before the beginning of the study, the horses were clinically, orthopaedically, sonographically (SDFT, DDFT), and radiologically (overview toe, lateromedial and dorsopalmar projection) examined by 2 independent veterinarians. The orthopaedic examination included inspection, palpation, and a lameness exam on hard and soft surface. Based on all examinations, horses with orthopaedic disorders or other diseases were excluded. Before any examination, the hooves were trimmed by the same certified farrier to ensure an equal hoof status.

The trim was performed by cleaning the frog and removing the brittle horn of the sole to show the length of the overgrown weight bearing margin, which was shortened following the level of the cleaned sole. Severe reorientation of the limb and straightening of the outer hoof wall was avoided. Horses with severe flares in the dorsal hoof wall were excluded.

**Assessment of wither height and DWA**
The wither height of all horses was assessed with a standardised [Albenisa: Handmeasure for horses, ALBENISA GmbH, Friedensstraße 13a, 06184 Kabelsketal, Germany] horse measuring stick marked with hand measures. A [Dallmer gauge: Dallmer Hoof Gauge, Dallmer GmbH + Co. KG, 59757 Arnsberg, Germany] was used to measure the DWA (Moleman et al., 2005). This gauge uses the ground plane and an area of contact on the dorsal hoof wall and measures the angle of the loaded foot. All measurements were performed three times by the same operator. For further analysis the mean values of all three measurements were used. The horses had to stand square and relaxed on a plane concrete surface.

**Radiographic examination**
The radiographic examinations were carried out by using a portable x-ray unit [Gierth HF80 MLul®: Gierth X-Ray International, Riesa, Sachsen, Germany] and a digital detector system [SCOPE-XXS 80C, Detector Canon CXDI-80C wireless: Canon Inc., Tokyo, Ohta-ku, Japan]. A standardised setup (60kV, 0.2mAs/s, focus-film distance 75cm) was followed. Initially, the hooves were permanently marked according to published guidelines to ensure a standardised centring of the radiation beam (Caudron et al., 1997). Two radiographs were acquired respectively for the left and the right front foot. First, a lateromedial radiograph with the x-ray beam centred in the midline of the dorsal hoof wall, 2 cm over the weight bearing margin to visualise the distal and the middle phalanx was produced (Caudron et al., 1997; Kummer et al., 2006). Second, the beam was centred on the MPJ to obtain a lateromedial projection representing the proximal phalanx, the sesamoid bones, and at least the distal third of the metacarpal bone. The horses were standing square with a straight body axis and relaxed with both forelimbs positioned parallel on a 6 cm podoblock [MetronPX podoblock: EponaTech LLC, Creston, CA, USA] with embedded reference marks for subsequent analyses (Rocha et al., 2004). If the podoblock was not in the examination window, the calibration aid [Metron Auto-Scaler: EponaTech LLC,
Creston, CA, USA] was attached in the region of the fetlock including the same reference points as the podoblock to calibrate the software for magnification and distortion of the radiographs. No sedation was necessary. All radiographs were directly monitored on the computer screen to check consistency of quality and projection according to guidelines published by Dyson et al. (2011). Radiograph image control involved the assessment of parallelism of the condyles of the middle and proximal phalanx, superimposition of the lateral and medial solar borders and the palmar aspects of the extensor process of the distal phalanx and clearly defined interphalangeal joint spaces.

**Ultrasound examination**

The ultrasound examination was carried out directly after the radiographic examination. For the examinations, a portable ultrasound unit [Honda electronics HS-1200V; Honda Electronics Co., LTD., Aichi 441-3193, Japan] and a variable frequency linear transducer [Honda electronics HLS 584M linear probe: Honda Electronics Co., LTD., Aichi 441-3193, Japan] (6.0-11MHz; Width: 40mm), set at 8.5 MHz and a field depth of 4 cm with a stand-off pad to ensure optimal coupling, were used. The palmar aspect of the metacarpus was clipped and scrubbed with alcohol. [Ultrasound coupling gel: DocCheck Ultraschall-Gel, DocCheck Medizinbedarf und Logistik GmbH, Weil im Schönbuch, Germany] was applied prior to and during the examination. The probe was placed at the most palmar aspect of the metacarpal region, perpendicular to its surface. Dividing the metacarpal region into different zones is an established method in equine practice to compare the morphology of the DDFT and SDFT throughout both their ranges where most pathologies are likely to occur (Denoix, 1994; Dowling et al., 2000; Dyson, 2002). Within each of the three previously described zones, specific points were chosen for examination. Transverse images of the SDFT and the DDFT were acquired at 8 cm (zone B1), 12 cm (zone A2), and 16 cm (zone B2) distal to the accessory carpal bone according to Padaliya et al. (2015) (Figure 1).

The probe was manipulated in all planes to obtain an optimal image showing the widest CSA possible of each tendon at the specific zone. To analyse the ultrasound images, a frozen representative image of the SDFT and the DDFT of each level was saved when the accurate identification and tracking of the outer margin of both flexor tendons was possible.

**Data analysis**

Parameters of interest, their references and interpretation are shown in Figure 1 and Table 1. The Dicom files generated during the radiographic examinations were converted into JEPPG files and imported into the software [MetronPXHoof®: EponaTech LLC, Creston, CA, USA].

![Fig. 1. Parameters of interest and their references.](image)

After calibration, the parameters of interest were measured three times by the same person and by following standardised references (Table 1). All ultrasound images were analysed using the image processing software [ImageJ: vers. 2.0.0-rc-39/1.50b; Build: 8dcf1e65a6 Copyright 2010-2017]. The CSA SDFT and the DDFT was measured three times by one operator by outlining the structures of interest with a cursor and then calculating the encompassed area. The person responsible for data analysis was not involved in data acquisition and was blinded to the hypothesis of this study. The average of all three measurements was used for further calculations.

**Statistical analysis**

Statistical analysis was carried out with the software [R: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria]. Significance tests for normally distributed data were performed using the ‘Welch t-test’. Mean and standard deviations were calculated for all parameters of interest. To assess the relationships between the measured variables, pairwise correlations were calculated (Pearson). Correlations between the variables based on the calculations were interpreted as followed: r<0.19 – no correlation, r >0.2 and <0.29 – weak correlation, r >0.3 and <0.49 – moderate correlation, r >0.5 and <0.69 – strong correlation, r >0.7 and <0.99 – very strong correlation, r = 1 – perfect correlation. A paired t-test was used to evaluate the left–right differences. The significance level was set to p<0.05.

**Results**

N = 30 horses were included into the calculations. Data were normally distributed. Mean value, standard deviation of all measures and p-value of the left–right differences between both forelimbs are shown in Table 2.
Table 1. Parameters of interest with their abbreviations, references and interpretation.

| Parameter (Unit) - Abbreviation | References | Increase | Decrease |
|---------------------------------|-----------|----------|----------|
| Dorsal metacarpophalangeal joint angle (°) - DMPJ | rotation centre at the condyles of the metacarpal bone (point 1) and the proximal phalanx (point 2), middle of the metacarpal bone in the most proximal aspect (point 3) | decreased extension in the MPJ | increased extension in the MPJ |
| Dorsal wall angle of the hoof (°) - DWA | midline of the dorsal hoof wall parallel to the horn tubules | steep hoof orientation | flat hoof orientation |
| Angle of the proximal phalanx in relation to the ground (°) - API | horizontal determined by Metron reference combined with a line through the rotation centre at the condyles and the middle of the proximal phalanx | steep orientation of the proximal phalanx | flat orientation of the proximal phalanx |
| Angle of the middle phalanx in relation to the ground (°) - APII | horizontal determined by Metron reference combined with a line through the rotation centre at the condyles and the middle of the middle phalanx | steep orientation of the middle phalanx | flat orientation of the middle phalanx |
| Angle of the distal phalanx in relation to the ground (°) - APIII | angulation of a line from the apex to the end of the palmar processes of the distal phalanx in relation to a horizontal determined by Metron references | steep orientation of the distal phalanx | flat orientation of the distal phalanx |
| Length of the proximal phalanx (cm) - LenPI | longest distance between proximal and distal joint surface | long proximal phalanx | short proximal phalanx |
| Length of the middle phalanx (cm) - LenPII | longest distance between proximal and distal joint surface | long proximal phalanx | short proximal phalanx |
| Cross-sectional area of the superficial digital flexor tendon (mm²) - CSA SDFT | tracking the outer margin of both flexor tendons in transverse ultrasound images | larger tendon | thinner tendon |
| Cross-sectional area of the deep digital flexor tendon (mm²) - CSA DDFT | tracking the outer margin of both flexor tendons in transverse ultrasound images | larger tendon | thinner tendon |

Table 2. Mean and standard deviations of all parameters and differences between the left and the right forelimb.

| Parameter | Left limb (mean ± SD) | Right limb (mean ± SD) | Diff. left-right (p-val.) |
|-----------|----------------------|------------------------|--------------------------|
| DWA (°)   | 49.45 ± 5.32         | 49.00 ± 4.47           | 0.11                     |
| APIII (°) | 4.20 ± 3.50          | 4.1 ± 3.14             | 0.29                     |
| API (°)   | 54.57 ± 6.90         | 50.31 ± 5.73           | 0.002                    |
| API (°)   | 69.89 ± 4.76         | 66.18 ± 6.34           | 0.01                     |
| DMPJ (°)  | 149.11 ± 5.33        | 148.16 ± 5.97          | 0.002                    |
| LenPII (cm)| 4.28 ± 0.24        | 4.34 ± 0.29            | 0.28                     |
| LenPI (cm)| 8.14 ± 0.52         | 8.12 ± 0.51            | 0.19                     |
| CSA SDFT 1B (mm²) | 7.99 ± 1.50 | 8.01 ± 1.47 | 0.95 |
| CSA SDFT 2A (mm²) | 7.81 ± 1.59 | 7.83 ± 1.42 | 0.96 |
| CSA SDFT 2B (mm²) | 8.21 ± 1.43 | 8.14 ± 1.23 | 0.83 |
| CSA DDFT 1B (mm²) | 10.48 ± 1.87 | 10.15 ± 1.69 | 0.50 |
| CSA DDFT 2A (mm²) | 9.88 ± 1.74 | 9.65 ± 1.56 | 0.61 |
| CSA DDFT 2B (mm²) | 14.91 ± 2.00 | 14.46 ± 1.98 | 0.41 |

A significant difference (p=0.002) between the DMPJ of the left and the right limb occurred. Less extension in the left MPJ was found. Additionally, a left–right difference occurred for the orientation of the proximal and middle phalanges, API (p=0.01) and APIII (p=0.002). At the left limbs a steeper orientation of the middle and proximal phalanx occurred. No significant bilateral differences were shown for the DWA, APIII, LenPI, LenPII, or the CSA SDFT/DDFT at any zone. An overview of the correlation between the DMPJ and the toe conformation or the CSA of the flexor tendons is given in Table 3.
Calculation of the interaction between the DWA and APIII with the DMPJ showed no correlation. The API, APII, LenI, and LenII showed the highest correlations with the DMPJ. At the left and in particular the right limb, the LenPI and the LenPII showed a moderate negative correlation with the DMPJ. The longer the proximal and middle phalanges, the smaller the DMPJ, indicating higher extension in this joint. Additionally, a moderate to strong correlation occurred between the DMPJ and the API and APII. The more upright the orientation of the proximal and middle phalanges, the greater the DMPJ, meaning less extension in this joint. No or only a very weak correlation between the DMPJ and the CSA of both flexor tendons was demonstrated at any level. A moderate correlation was shown between the DMPJ and the wither height ($r = -0.31$, $p=0.04$). Neither sex nor age had an impact on the DMPJ ($r < 0.19$).

**Discussion**

Although in the current examinations no left–right differences in the dorsal wall angle of the hoof or the sagittal orientation of the distal phalanx were shown, a significant uneven angulation of the middle and proximal phalanx and higher extension in the MPJ of the right limb was found. Therefore, hypothesis 1 was not confirmed. Other authors have stated the prevalence of uneven feet to be on average 5.3%, without providing specific data for the fetlock (Ducro et al., 2009a). Most previous studies were performed to compare left–right symmetry in hooves. It has been stated that foals develop unevenness in the foot conformation as a consequence of an uneven loading pattern caused by a preference to protract the same limb systematically while grazing (Heel et al., 2006). Moreover, studies have shown a relationship between uneven feet and laterality connected with a side preference for trot-canter transition in young horses (Deuel and Lawrence, 1987; van Heel et al., 2010). Considering handedness in horses, the same authors found that the right forelimb is preferentially used for support, and, as the trailing limb, it experiences greater stress than the leading left forelimb (Deuel and Lawrence, 1987; van Heel et al., 2010). Based on these findings the authors of the current study assume that lateralised grazing and motor behaviour determining handiness and uneven load bearing in horses might also lead to asymmetry in the DMPJ, API, and APII with higher extension in the right MPJ. This is supported by the findings of previous radiographic examinations in 75 sound horses, which also showed a lower palmar angle of the middle (APII) and proximal (API) phalanx in the right feet (Hagen et al., 2018). However, the correlation between these observations and lateralised grazing or motor behaviour requires further investigation. The relevance of 1° to 3° bilateral difference in DMPJ, APII or API on the load of joints, tendons or ligaments remains unclear. For differences in the palmar angle (APIII) of the distal phalanx it was demonstrated that for a 1° change in APIII the forces experienced by the DDFT changed by 4% (Eliashar et al., 2004). Similar calculation about the relation between a 1° change in DMPJ, API, and APII are lacking, in particular for left-right differences in bilateral feet. Nevertheless, uneven feet conformation in horses is a frequently examined topic assumed to be of clinical relevance. It was shown that differences in the contralateral foot conformation are related to different lever arms affecting the digital joints.

**Table 3. Correlation between the parameters of interest, with $r = 1$ perfect correlation, 0.7–0.99 very strong correlation, 0.5–0.69 strong correlation, 0.3–0.49 moderate correlation, 0.2–0.29 weak correlation, ≤0.19 no correlation.**

| Parameter       | DMPJ left |               | DMPJ right |               | Correlation          |
|-----------------|-----------|---------------|------------|---------------|----------------------|
|                 | Corr coef ($r$) | P value | Corr coef ($r$) | P value |                      |
| LenPI           | -0.30     | 0.03          | -0.45      | 0.01         | moderate to strong correlation |
| LenPII          | -0.28     | 0.04          | -0.44      | 0.01         |                      |
| API             | 0.41      | 0.02          | 0.38       | 0.03         |                      |
| APII            | 0.63      | <0.001        | 0.40       | 0.02         |                      |
| DWA             | -0.17     | 0.34          | 0.05       | 0.77         |                      |
| APIII           | -0.17     | 0.34          | 0.14       | 0.43         |                      |
| CSA SDFT 1B     | -0.03     | 0.88          | -0.01      | 0.98         |                      |
| CSA DDFT 2A     | 0.11      | 0.59          | 0.21       | 0.29         |                      |
| CSA SDFT 2B     | 0.14      | 0.51          | -0.13      | 0.50         |                      |
| CSA DDFT 1B     | -0.08     | 0.68          | -0.01      | 0.98         |                      |
| CSA SDFT 2A     | 0.01      | 0.96          | 0.05       | 0.81         |                      |
| CSA SDFT 2B     | -0.02     | 0.94          | 0.21       | 0.29         |                      |

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In addition, the study by Ducro et al. (2009b) showed a relationship between uneven foot conformation and a shortened competitive life. However, the authors want to stress that no definite correlation of the height of the animals and the DMPJ was found. An increasing wither height was associated with higher extension in the MPJ, which has been confirmed with a mild positive correlation of wither height and LenPI, LenPII. In this context, weighing the horse would have been more valuable to the correlation with the DMPJ. However, a precise weighing of the animals was not possible at the available location.

**Study design and morphometric measurements**

The examinations and measurements used in this study are commonly used techniques in equine practice. A standardised protocol for the radiographic and ultrasound examinations was followed. All horses were cooperative and calm.

The radiographic measurements with [MetronPXHoof: EponaTech LLC, Creston, CA, USA] were already evaluated as an objective method to analyse morphometric parameters of the equine foot (Rocha et al., 2004). However, the authors want to stress that radiography is an examination technique that provides a two-dimensional image of a three-dimensional object representing a static snapshot of a dynamic situation. Due to this limitation, projection obliquity, superposition and distortion influence the measurements and might interact with the relevance of the observed 1° changes in DMPJ. However, due to the standardised measuring and analysis protocols the measuring error for this parameter was below 1° and obtained results are in line with previous findings where the same technique was used for data acquisition and analysis (Hagen et al., 2018). In this study calibration aids were used and all images were checked for quality. Aid lines were drawn onto the radiographs using clear bony protuberances as a guide, and all measurements were taken by the same experienced operator, because bony references used for analysing the angles are subjective and difficult to standardise. However, the high standard deviation in the calculated angles might be in part related to the measurements. Nevertheless, the measure failure is not considered clinically relevant by other authors (Rocha et al., 2004).

The precision of ultrasound image acquisition and analysis to assess the CSA of both flexor tendons at different levels was tested in advance with the given setup under the same conditions and with the same operator. The overall concordance correlation coefficient for image acquisition was between 0.84 and 0.98 (CSA DDFT 2A) and > 0.99 (CSA SDFT) (Kojah et al., 2017). The OCCC for the analysis of the CSA was > 0.99 for all zones at each tendon (Kojah et al., 2017). These values and those stated by other authors prove the high accuracy and precision of the ultrasound examination performed in this study (Pickersgill et al., 2001).

Due to the nature of radiographic and ultrasound imaging, presented results are only valid for static conditions. The study provides only a static evaluation of a dynamic situation. Load of the limbs and weight shift might interact with the DMPJ and the parameters found to be correlated to the extension of the fetlock. Furthermore, results are obtained only for a specific
population of horses. Examinations in other populations might differ in particular for the values obtained for the length and angle of the phalanges and the CSA of the SDFT and DDFT. Additionally, left-right differences might occur differently in other horses.

This study provides additional data about the angulation of the MPJ and how it is related to the toe conformation. Significant left-right differences in the DMPJ occurred for the individual horse. In the authors’ opinion, the length and the sagittal orientation of the proximal phalanges might have a greater impact on the DMPJ than the hoof conformation, represented in the current study by the DWA and the APIII. In a clinical context, it might be useful to focus more on the conformation of the equine pastern during static and dynamic evaluation of the horse as a basis for orthopaedic treatment, trimming or shoeing. Further research on this topic is required.

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Conflict of interest

The authors declare that there is no conflict of interests.

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