Annals of Anatomy 209 (2017) 1–10

Contents lists available at ScienceDirect

Annals of Anatomy

journal homepage: www.elsevier.com/locate/aanat

RESEARCH ARTICLE

Fetal development of the pulley for muscle insertion tendons: A review and new findings related to the tensor tympani tendon

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ARTICLE INFO

Article history:
Received 6 August 2016
Received in revised form
10 September 2016
Accepted 10 September 2016

Keywords:
Development
Human fetus
Pulley
Tendon
Tensor tympani

ABSTRACT

The existence of hard tissue pulleys that act to change the direction of a muscle insertion tendon is well known in the human body. These include (1) the trochlea for the extraocular obliquus superior muscle, (2) the pterygoid hamulus for the tensor veli palatini muscle, (3) the deep sulcus on the plantar aspect of the cuboid bone for the peroneus longus tendon, (4) the lesser sciatic notch for the obturator internus muscle, and (5) the bony trochleariformis process for the tensor tympani muscle tendon. In addition, (6) the stapedius muscle tendon shows a lesser or greater angulation at the pyramidal eminence of the temporal bone. Our recent studies have shown that the development of pulleys Nos. 1 and 2 can be explained by a change in the topographical relationship between the pulley and the tendon, that of pulley No. 3 by the rapidly growing calcaneus pushing the tendon, and that of pulley No. 4 by migration of the insertion along the sciatic nerve and gluteus medius tendon. Therefore, in Nos. 1–4, an initially direct tendon curves secondarily and obtains an attachment to the pulley. In case No. 6, the terminal part of the stapedius tendon originates secondarily from the interzone mesenchymal tissue of the incudostapedial joint. In the case of pulley No. 5, we newly demonstrated that its initial phase of development was similar to No. 6, but the tensor tympani tendon achieved a right-angled turn under guidance by a specific fibrous tissue and it migrated along the growing malleus manubrium.

1. Introduction

1.1. Is a curved tendon likely in fetal development?

The existence of hard tissue pulleys that act to change the direction of a muscle insertion tendon is well known in the human body, and is considered to be one type of various enthesis morphologies (Benjamin et al., 1995). In the present study, we describe the change in direction of the tensor tympani tendon at the future trochleariformis process of the temporal bone, with reference to the development of (1) the trochlea for the obliquus superior muscle of the eye, (2) the hamulus of the pterygoid for the tensor veli palatini muscle, (3) the deep sulcus or facet on the plantar aspect of the cuboid bone for the peroneus longus, and (4) the lesser sciatic notch for the obturator internus muscle tendon. In these 5 pulleys, the insertion tendon shows an almost right-angled turn (the tensor veli palatini and peroneus longus muscles) or an acute turn (the tensor tympani, extraocular obliquus superior, and obturator internus muscles). In addition, the stapedius tendon exhibits a lesser or greater angulation at the pyramidal eminence, in which a bony canal for the muscle opens to the tympanic cavity.

Generally, development of the tendon follows that of the muscle belly in accordance with specific signaling pathways for tendons (Schweitzer et al., 2001; Murchison et al., 2007; Pryce et al., 2009), even though the muscle belly and tendon share a common cell lineage (Brent et al., 2003, 2005). In the initial stage of development, the muscle belly and its insertion tendon seem to require a linear

Abbreviations: TT, tensor tympani; CRL, crown-rump length; CTN, chorda tympani nerve; FN, facial nerve; GO, os goniale; GPN, greater petrosal nerve; IN, incus; IH, interhyale; LPM, lateral pterygoid muscle; LSC, lateral semicircular canal; MA, malleus; MC, Meckelís cartilage; MN, mandibular nerve; OG, otic ganglion; PG, parotid gland; PTC, pharyngotympanic tube cartilage; RC, Reichertís cartilage; ST, stapes; STA, superficial temporal artery; STM, stapedius muscle; STT, stapedius tendon; TC, tympanic cavity; TEM, temporalis muscle; TM, tympanic membrane; TTM, tensor tympani muscle; TTT, tensor tympani tendon; TY, tympanic bone.

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http://dx.doi.org/10.1016/j.aanat.2016.09.001
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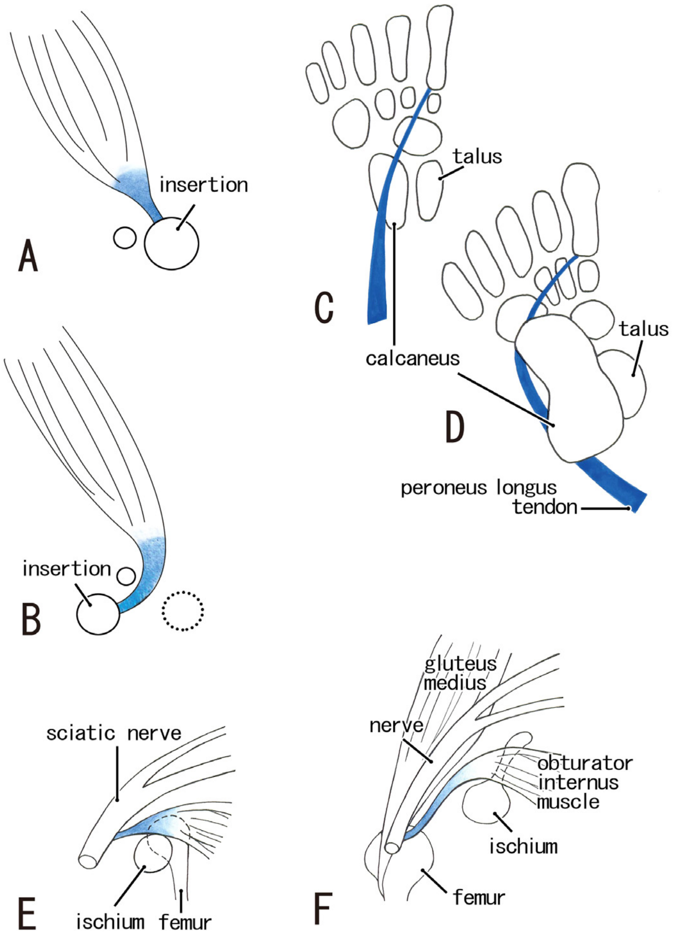

Fig. 1. A set of multiple line drawings for review of developmental process of the changing direction of tendons.
Panels A and B display a pattern of development of the pulley: the topographical relationship is changed secondarily between the insertion target and the future pulley structure (i.e., the trochlea and hamulus). Panels C and D exhibit development of the peroneus longus tendon. The underdeveloped calcaneus allows the straight course of tendon to the toe. However, the expanding calcaneus pushes the tendon to the cuboid bone. Panels E and F show development of the obturator internus tendon. The obturator tendon first attaches to the sciatic nerve (panel E) and next joins the gluteus medius tendon (panel F). Topographical relation between the femur head and ischium is also drastically changed.

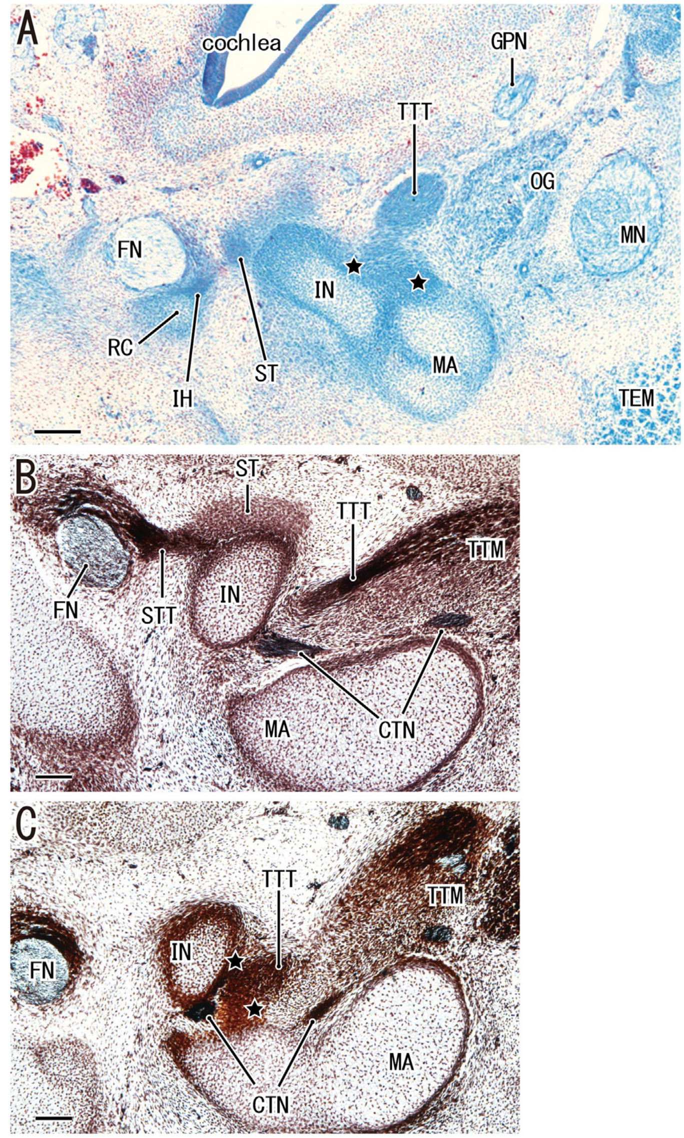

Fig. 2. Early phase of the tensor tympani muscle insertion.
Azan staining (panel A) and silver staining (panels B and C). Horizontal sections of 2 specimens. Panel A (CRL, 16 mm; 6 weeks) displays the tensor tympani tendon (TTT) attaching to an interzone mesenchymal tissue (stars) between the malleus (MA) and incus (IN). Panel B (CRL, 23 mm; 7 weeks) exhibits a long straight course of the tensor tympani tendon. The stapedius tendon (STT) is also seen. Panel C, 0.05 mm inferior to panel A, the tensor tympani tendon joins the interzone mesenchymal tissue (stars). The chorda tympani nerve (CTN) runs near the mesenchymal tissue. All panels are prepared at the same magnification (scale bars, 0.1 mm). The other abbreviation, see the 'Abbreviations' section.

arrangement from the muscle origin to the insertion, since tensile stress from the muscle belly is essentially important for the development and maintenance of tendon morphology (Kjaer et al., 2006, 2009; Mackey et al., 2008). Therefore, a drastic change in the direction of the tendon at the pulley is most likely to occur "secondarily" after establishment of the basic, linear arrangement of the muscle and tendon. The straight tendon is also likely to determine, in part, the morphology of the bone (Thomopoulas et al., 2010).

1.2. When and how does the tendon change direction in embryos?

According to Katori et al. (2011), migration of the tendon insertion (Fig. 1A and B) is critically important for development of the pulley for the superior obliquus tendon of the eye (delayed rotation of the eyeball) as well as for the tensor veli palatine tendon (delayed posterior shift of the soft palate). Thus, the trochlea and hamulus become a pulley secondarily after formation of the direct tendon. Likewise, in the embryo at 5 weeks, the peroneus longus tendon takes a straight course similar to the long flexor tendons beneath the underdeveloped, flat calcaneus without its tuber or heel (Yamamoto et al., 2016). Thus, at 6 weeks, the expanding calcaneus secondarily pushes the peroneus longus tendon to the cuboid bone (Fig. 1C and D). According to Naito et al. (2015), the obturator internus tendon changes its insertion from the sciatic nerve sheath, via the gluteus medius tendon, to its final insertion to the trochanteric fossa of the femur (Fig. 1E and F). The gemellus muscles also provide guidance for the growing obturator tendon. During transition of the obturator tendon attachment, (1) the topographical relationship between the femur head and ischium changes and (2) the tendon angulation becomes acute at the lesser sciatic notch. In addition, according to Rodríguez-Vázquez (2005, 2009), the stapedius tendon first provides the axis of a Y-shaped transient structure. The two wings of the "Y" (i.e., the interzone mesenchyme) connect the initial stapes and incus for the future incudostapedial joint. Later, one of the two wings disappears and the other parts