

Acta Medica Okayama

Volume 41, Issue 6

1987

Article 5

DECEMBER 1987

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Abstract

In the Japanese, Formosan and crab-eating monkeys, the dorsal metatarsal arteries and their lateral distal perforating branches were well developed and supplied, directly or via the catella plantaris distalis, the plantar digital arteries. In the black ape, the plantar digital arteries arose from the medial plantar artery. The plantar metatarsal arteries of these monkeys, including the black ape, arose from the catella plantaris proximalis or deep plantar arch and were classified into the superficial plantar metatarsal (sM), superficial plantar intermetatarsal (sI), deep plantar metatarsal (dM) and deep plantar intermetatarsal (dI) arteries in relation to the interosseous muscles and metatarsal bones. This classification largely coincides with that of the human hand and foot (Murakami, 1969, 1971) and the monkey hand (Nakai et al., 1987).

KEYWORDS: Monkey foot, plantar metatarsal arteries, perforating branches, catellage plantares, deep plantar arch, plantar digital arteries

*PMID: 3439481 [PubMed - indexed for MEDLINE]

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Pedal Arteries of Monkeys, with Special Reference to the Plantar Metatarsal Arteries

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In the Japanese, Formosan and crab-eating monkeys, the dorsal metatarsal arteries and their lateral distal perforating branches were well developed and supplied, directly or via the catella plantaris distalis, the plantar digital arteries. In the black ape, the plantar digital arteries arose from the medial plantar artery. The plantar metatarsal arteries of these monkeys, including the black ape, arose from the catella plantaris proximalis or deep plantar arch and were classified into the superficial plantar metatarsal (sM), superficial plantar intermetatarsal (sI), deep plantar metatarsal (dM) and deep plantar intermetatarsal (dI) arteries in relation to the interosseous muscles and metatarsal bones. This classification largely coincides with that of the human hand and foot (Murakami, 1969, 1971) and the monkey hand (Nakai *et al.*, 1987).

Key words : Monkey foot, plantar metatarsal arteries, perforating branches, catellae plantares, deep plantar arch, plantar digital arteries

The deep layer of the human foot is generally regarded as being supplied by the plantar metatarsal arteries (1, 2). Murakami classified the plantar metatarsal arteries in relation to the interosseous muscles and metatarsal bones into the (a) superficial plantar metatarsal (sM), (b) superficial plantar intermetatarsal (sI), (c) deep plantar metatarsal (dM) and (d) deep plantar intermetatarsal (dI) arteries (3). A similar classification of arteries of the human hand (4) was also applicable to the monkey hand (5). The present paper describes these four types of arteries in monkey feet.

Materials and Methods

An aged Japanese monkey (*Macacus fuscatus*), an aged Formosan monkey (*Macacus cyclopsis*), an aged crab-eating monkey (*Macacus cynomolgus*) and

an aged black ape (*Cynopithecus niger*) were obtained from the Ritsurin Park Zoo (Takamatsu, Kagawa, Japan) upon their death. They were fixed with 10% formalin by vascular perfusion. After immersion in an ethanol bath for two years or longer, the left foot of each monkey was dissected.

Results

In the monkeys studied, the first dorsal metatarsal artery (D1, Figs. 1-3) arose from the superficial dorsal pedal artery, and the second to fourth dorsal metatarsal arteries (D2-D4, Figs. 1-3) arose from the deep dorsal pedal artery. In the *Cynopithecus niger*, the dorsal metatarsal arteries were poorly developed, and their main branches gave rise to the proximal perforating branches (p1-p4, Fig. 4).

The dorsal metatarsal arteries (D1-D4,

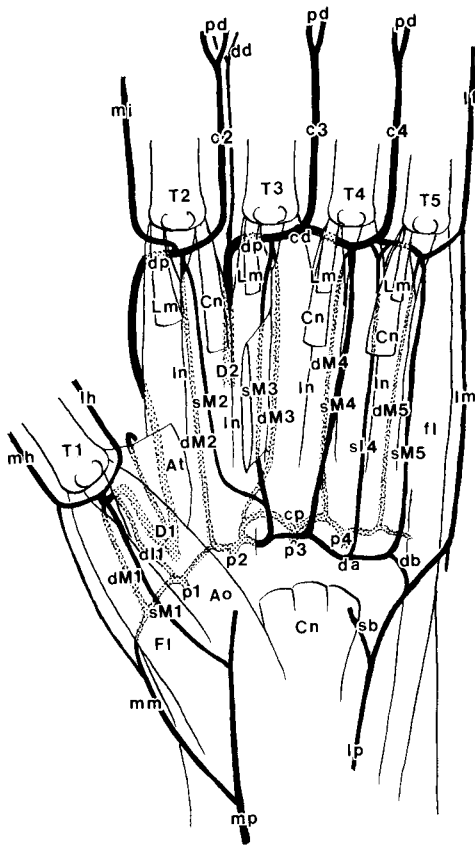


Fig. 1 A diagram showing the arterial pattern in the deep planta of the *Macacus fuscatus* (view from the plantar side). For abbreviations, see footnotes.

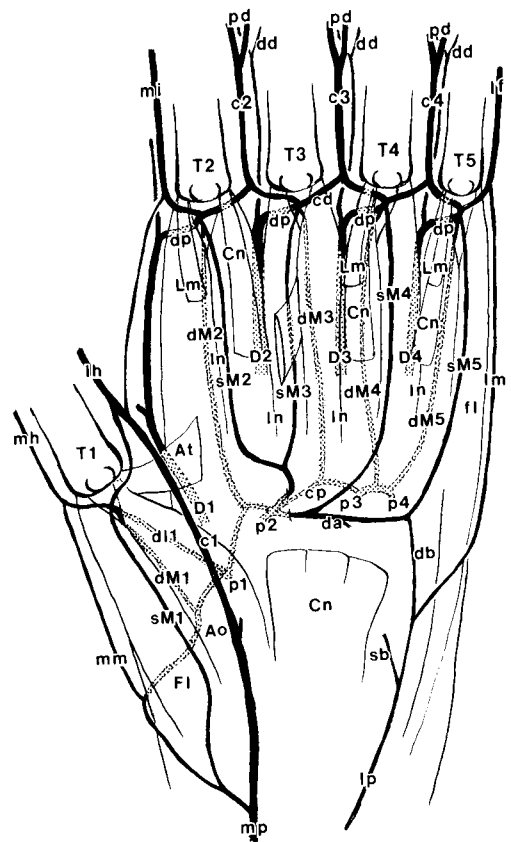


Fig. 2 A diagram showing the arterial pattern in the deep planta of the *Macacus cyclopsis* (view from the plantar side). For abbreviations, see footnotes.

Figs. 1-3), including the first one (D1, Figs. 1-3), descended along the dorsal surface of the interosseous muscles (In, Figs. 1-4) and gave off the proximal and distal perforating

branches (p1-p4 and dp, Figs. 1-4). The proximal perforating branches perforated the proximal end of the intermetatarsal spaces and formed the catella plantaris proximalis (cp,

Abbreviations used. *Toes and Muscles*: T1-T5, First to fifth toes; Ao, Oblique head of the adductor hallucis muscle; At, Transverse head of the adductor hallucis muscle; Cn, Contrahentes muscles (adductor digiti muscles); Fl, Flexor hallucis brevis muscle; In, Interosseous muscles; Lm, Lumbrical muscles; fl, Flexor digiti minimi brevis muscle.

Arteries: C1-C4, First to fourth plantar digital arteries; D1-D4, First to fourth dorsal metatarsal arteries; dl1-dl4, First to fourth deep plantar intermetatarsal arteries; dM1-dM5, First to fifth deep plantar metatarsal arteries; sM1-sM5, First to fifth superficial plantar intermetatarsal arteries; p1-p4, First to fourth proximal perforating branches; cd, Catella plantaris distalis; cp, Catella plantaris proximalis; da, Deep plantar arch; db, Deep branch of the lateral plantar artery; dd, Proper dorsal digital arteries of the second to fifth toes except those of the medial side of the second toe and lateral side of the fifth toe; dp, Distal perforating branches; lh, Lateral proper plantar digital artery of the first toe (hallux); lf, Lateral proper plantar digital artery of the fifth toe; lm, Lateral marginal plantar artery; lp, Lateral plantar artery; mh, Medial proper plantar digital artery of the first toe; mi, Medial proper plantar digital artery of the second toe; mm, Medial marginal plantar artery; mp, Medial plantar artery; pd, Proper plantar digital arteries of the second to fifth toes except those of the medial side of the second toe and the lateral side of the fifth toe; sb, Superficial branch of the lateral plantar artery.

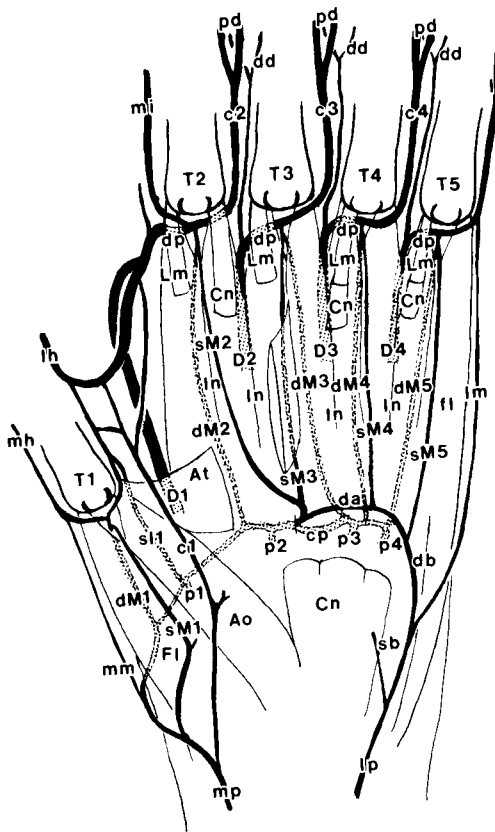


Fig. 3 A diagram showing the arterial pattern in the deep planta of the *Macacus cynomolgus* (view from the plantar side). For abbreviations, see footnotes.

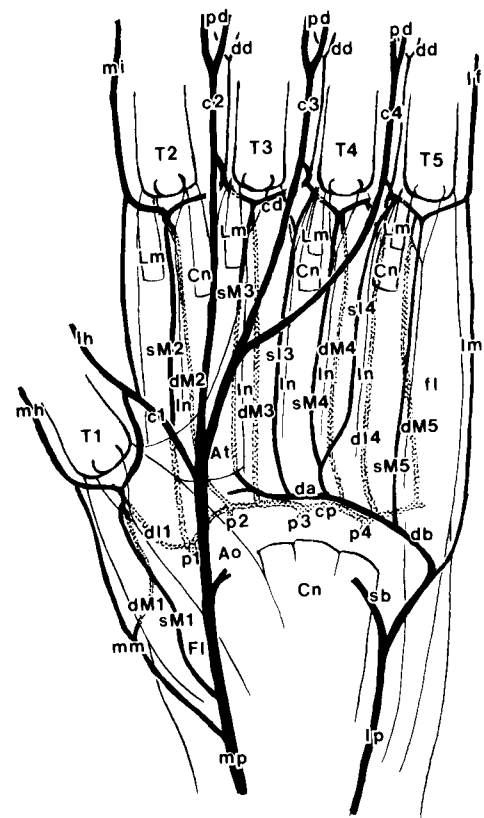


Fig. 4 A diagram showing the arterial pattern in the deep planta of the *Cynopithecus niger* (view from the plantar side). For abbreviations, see footnotes.

Figs. 1-4) deep in the interosseous muscles (In, Figs. 1-4). The distal perforating branches (dp, Figs. 1-3) were paired vessels (medial and lateral), which ran around the necks of the metatarsal bones and continued, directly or via the catella plantaris distalis (cd, Figs. 1, 2, 4), into the plantar digital arteries (c2-c4, Figs. 1, 2, 4) or proper plantar digital arteries (lf, mi, pd, Figs. 1, 2, 4). The medial distal perforating branches (dp, Figs. 1-3) were thicker than the lateral ones.

The catella plantaris distalis (cd, Figs. 1, 2, 4) was located on the plantar surface of the interosseous muscles (In, Figs. 1-4) or on the dorsal surface of the contrahentes (Cn, Figs. 1-4) and lumbrical (Lm, Figs. 1-4) muscles at a level just proximal to the

necks of the metatarsal bones, and its typical form was observed in the *Macacus cyclopsis* and *Cynopithecus niger* (Figs. 1, 4).

The proper plantar digital arteries in both sides of each toe (pd, Figs. 1-4) were thicker than the proper dorsal digital arteries (dd, Figs. 1-4). These proper plantar digital arteries arose from the plantar digital arteries (c2-c4, Figs. 1-4), medial and lateral marginal plantar arteries (mm and lm, Figs. 1-4) or plantar metatarsal arteries (sm1-sm5, sl1-sl4, dm1-dm5 and dl1-dl4, Figs. 1-4, see below). The dorsal proper digital arteries (dd, Figs. 1-4) arose from the dorsal metatarsal arteries (D1-D4, Figs. 1-3). In the *Cynopithecus niger*, the dorsal metatarsal arteries were poorly developed

(see above), so that the proper dorsal digital arteries (dd, Fig. 4) arose from the catella plantaris distalis (cd, Fig. 4).

The medial and lateral plantar arteries (mp and lp, Figs. 1-4) arose from the posterior tibial artery. The medial plantar artery (mp) ran along the medial border of the flexor digitorum brevis muscle (Fl, Figs. 1-4), and gave off the medial marginal plantar artery (mm, Figs. 1-4). The medial plantar artery, when developed, gave rise to the first to fourth plantar digital arteries (c1-c4) supplying most of the proper plantar digital arteries of the first to fifth toes (lh and pd) (Fig. 4). The lateral plantar artery (lp) descended along the lateral border of the flexor digitorum brevis muscle (fl, Figs. 1-4) and gave off the superficial and deep branches (sb and db, Figs. 1-4) and the lateral marginal plantar artery (lm, Figs. 1-4). The superficial branch (sb) connected with the third or fourth plantar digital artery (c3 or c4, Fig. 4) and formed the superficial plantar arch on the plantar surface of the flexor digitorum brevis muscle. The deep branch (dp) connected with a branch of the catella plantaris proximalis (cp) and formed the deep plantar arch (da) on the plantar surface of the interosseous muscles (In) or on the dorsal surface of the contrahentes muscles (Cn) (Figs. 1-4).

The plantar metatarsal arteries arose from the deep plantar arch (da) or catella plantaris proximalis (cp) (Figs. 1-4). By their relationship to the interosseous muscles and metatarsal bones, the plantar metatarsal arteries (except those in the hallux, see below) could be classified into: (a) the second to fifth superficial plantar metatarsal (sM2-sM5) arteries descending on the plantar surface of the interosseous muscles (In) along the second to fifth metatarsal bones, (b) the second to fourth superficial plantar intermetatarsal (sI2-sI4) arteries descending on the plantar surface of the interosseous

muscles (In) along the second to fourth intermetatarsal spaces, (c) the second to fifth deep plantar metatarsal (dM2-dM5) arteries descending in the interosseous muscles (In) along the second to fifth metatarsal bones, and (d) the second to fourth deep plantar intermetatarsal (dI2-dI4) arteries descending deep in the interosseous muscles (In) along the second to fourth intermetatarsal spaces (Figs. 1-4).

The hallux or first toe was provided with the adductor hallucis muscle (At : transverse head; Ao : oblique head) (Figs. 1-4). This muscle arose from the tarsus and third metatarsal bone and attached to the lateral side of the hallux, and the first superficial plantar intermetatarsal (sI1) artery descended on the latero-dorsal surface of the oblique head (Ao) of the adductor hallucis muscle (Fig. 3). The first deep plantar intermetatarsal (dI1) artery descended along the first metatarsal bone or on the medio-dorsal surface of the oblique head (Ao) of the adductor hallucis muscle (Figs. 1-3). The first deep plantar metatarsal (dM1, *priceps hallucis*) artery descended on the plantar surface of the first metatarsal bone and was covered by the adductor hallucis (oblique head, Ao) or flexor hallucis brevis muscle (Fl) (Figs. 1-4). The first superficial plantar (sM1) artery arose from the medial plantar artery (mp) on the plantar surface of the adductor hallucis (oblique head, Ao) or flexor hallucis brevis muscle (Fl) (Figs. 1-4).

The sM, sI, dM and dI arteries were independent. Their development varied from case to case. The poorly developed sM, sI, dM and dI arteries terminated only in the mid-region of the metatarsus. In contrast, the well developed sM, sI, dM and dI arteries reached the metatarsophalangeal joints or connected with the catella plantaris distalis (cd) or distal perforating branches (dp) (Figs. 1-4). The well developed sM, sI, dM and dI arteries, together with the main arter-

ies of the toes, are illustrated in Figures 1-4 and described below.

Macacus fuscatus (Fig. 1). The first dorsal metatarsal artery (D1) and its medial and lateral distal perforating branches were well developed and became the proper plantar digital arteries of the first toe (lh and mh), the proper plantar digital artery of the medial side of the second toe (mi) and the second plantar digital artery (c2). The second dorsal metatarsal artery (D2) and its lateral distal perforating branch were more developed and formed the catella plantaris distalis (cd) between the third and fifth metatarsal bones. This catella gave off the third and fourth plantar digital arteries (c3 and c4) and the lateral proper plantar digital artery of the fifth toe (lf).

The first to fourth proximal perforating branches (p1-p4) formed the catella plantaris proximalis (cp). A branch of the second proximal perforating branch (p2) connected with the deep plantar branch (db) of the lateral plantar artery (lp) and formed the deep plantar arch (da). The catella plantaris proximalis (cp) received a branch of the medial marginal plantar artery (mm) and produced the dM1, dI1, dM2, dM3, dM4 and dM5 arteries. A branch of the medial plantar artery (mp) descended on the plantar surface of the flexor hallucis brevis muscle (F1) and became the sM1 artery.

Macacus cyclopsis (Fig. 2). The first to fourth dorsal metatarsal arteries (D1-D4) and their distal lateral perforating branches (dp) were well developed and formed the catella plantaris distalis (cd) between the second and fifth metatarsal bones. This artery gave off the medial proper plantar digital artery of the second toe (mi), the second to fourth plantar digital arteries (c2-c4) and the lateral proper plantar digital artery of the fifth toe (lf). The lateral proper plantar digital artery of the first toe (lh) arose from the first plantar digital artery (c1) de-

rived from the medial plantar artery (mp). The medial proper plantar digital artery of the first toe (mh) arose from the confluence of the dI1, dM1 and sM1 arteries.

The first or fourth proximal perforating branches (p1-p4) formed the catella plantaris proximalis (cp). A branch of the second proximal perforating branch (p2) connected with the deep plantar branch (db) of the lateral plantar artery (lp) and formed the deep plantar arch (da). The catella plantaris proximalis (cp) received a branch of the medial marginal plantar artery (mm) and produced the dM1, dI1, dM2, dM3, dM4 and dM5 arteries. The deep plantar arch (da) yielded the sM2, sM3, sM4 and sM5 arteries.

Macacus cynomolgus (Fig. 3). The first to fourth dorsal metatarsal arteries (D1-D4) and their lateral distal perforating branches (dp) were well developed and gave rise to the medial proper plantar digital artery of the second toe (mi), the second to fourth plantar digital arteries (c2-c4) and the lateral proper plantar digital artery of the fifth toe (lf). Each of the distal perforating branches (dp) was independent, so that no catella plantaris distalis was formed. The lateral proper plantar digital artery of the first toe (lh) arose directly from the first dorsal metatarsal artery (D1). The medial proper plantar digital artery of this toe (mh) arose from the confluence of the dM1 and sM1 arteries.

The first to fourth proximal perforating branches (p1-p4) formed the catella plantaris proximalis (cp) between the first and fifth metatarsal bones. A branch of the second proximal perforating branch (p2) connected with the deep plantar branch (db) of the lateral plantar artery (lp) and formed the deep plantar arch (da). The catella plantaris proximalis (cp) received a branch of the medial marginal plantar artery (mm) and produced the dM1, sI1, dM2, dM3, dM4 and dM5 arteries. The deep plantar arch (da) yielded the sM2, sM3, sM4 and sM5 arter-

ies.

Cynopithecus niger (Fig. 4). The medial plantar artery (mp) was fully developed and gave rise to the first to fourth plantar digital arteries (c1-c4). These arteries were reinforced by the catella plantaris distalis (cd), which was formed by the sM, dM, sI and dM arteries (see below) and extended between the second and fifth metatarsal bones. The medial proper plantar digital artery of the second toe (mi) and the lateral proper plantar digital artery of the fifth toe (lf) arose from this catella. The lateral proper plantar digital artery of the first toe (lh) arose from the first plantar digital artery (c1). The medial proper plantar digital artery of this toe (mh) arose from the confluence of the sM1, dM1 and dI1 arteries.

The first to fourth proximal perforating branches (p1-p4) formed the catella plantaris proximalis (cp) between the first and fifth metatarsal bones. The deep plantar branch (db) of the lateral plantar artery (lp) solely formed the deep plantar arch (da), without receiving any branch from the catella plantaris proximalis (cp). The catella plantaris proximalis (cp) produced the dI1, sM2, dM2, dM3, dI4 and dM5 arteries. The deep plantar arch (da) yielded the sM3, sI3, sM4 and sM5 arteries. The medial marginal plantar artery (mm) gave off the dM1 artery. The medial plantar artery (mp) gave off the sM1 artery.

Discussion

This paper describes the vascular architecture of the plantar and dorsal layers of the foot and its digits of the *Macacus fuscatus*, *Macacus cyclopsis*, *Macacus cynomolgus* and *Cynopithecus niger*. The basic structure is typologically similar to that of the human hand (4, 9) and foot (3, 6). In these monkeys, the main arteries of the toes are

the proper plantar digital arteries. However, the main routes to the proper plantar digital arteries or their parent plantar digital arteries showed some difference among the species. In the *Macacus fuscatus*, the third and fourth plantar digital arteries arose from the medial distal perforating branch of the second dorsal metatarsal artery. As far as we know, no one has reported such an unusual second dorsal metatarsal artery with wide distribution in any animal, including the man. In the *Macacus cyclopsis*, the plantar digital arteries arose from the dorsal metatarsal arteries via the catella plantaris distalis. This pattern has been reported in the foot of the *Macacus rhesus* (7). In the *Macacus cynomolgus*, the plantar digital arteries arose from the corresponding lateral distal perforating branches of the dorsal metatarsal arteries. A similar pattern has been reported in the foot of the *Semnopithecus maurus* (7). In the *Cynopithecus niger*, the plantar digital arteries arose directly from the medial plantar artery. This pattern is rather rare in the monkey foot (7), but it is usual in the human and monkey hand where the proper palmar digital arteries or their parent palmar digital arteries usually arise from the radial, median or ulnar artery (4, 5, 9). In the human foot, the plantar digital arteries almost always arise from the plantar metatarsal arteries (3, 6). A similar pattern has been reported in the foot of the *Gorilla gina* (7).

This study shows that the vascular architecture of the deep layer in the foot of the *Macacus fuscatus*, *Macacus cyclopsis*, *Macacus cynomolgus* and *Cynopithecus niger* is similar to the structure in the human hand and foot (3, 4), and in the hand and foot of other monkeys such as *Macacus rhesus* (7, 8, 10). The vascular system of the deep planta in the monkeys studied is composed of the superficial and deep arteries. The superficial arteries comprise the sM and sI vessels and correspond to the Aa. metatarsae plantares

profundae of Nishi (7) or the Aa. metatarsae plantares secundariae of Koch (10). The deep arteries comprise the dM and dI arteries and correspond to Rr. metatarsae plantares of Nishi (7) or the Aa. metatarsae plantares of Koch (10).

The superficial (sM and sI) and deep (dM and dI) arteries in the deep planta have generally been called the plantar metatarsal arteries (1, 2). However, this study shows that the plantar metatarsal arteries in the monkey foot, as in the human hand and foot (3, 4) and also in the monkey hand (5), can be classified into four types of arteries (sM1-sM5, sI1-sI4, dM1-dM5 and dI1-dI4) in relation to the muscles and bones. In the monkeys studied, the sM and dI arteries are constant vessels, while the sI and dI arteries are rather poorly developed. In contrast, the forepaw and hindpaw of some lower animals such as the dog and cat have well developed sI and dI arteries (unpublished data). In the human hand and foot, the dM and dI arteries sometimes are fully developed and become the main digital arteries (3, 4). In particular, the human princeps pollicis or hallucis artery is the dM1 artery (3, 4). Nishi observed well developed plantar metatarsal arteries in the *Hylobates leuciscus*, *Simia satyrus* and *Gorilla gina* (7). Judging from his description, the plantar metatarsal arteries of the *Hylobates* and the *Gorilla* correspond to the sM arteries, and those of the *Simia* to the sI arteries.

The sM arteries, like those of the human hand and foot (3, 4) and also those of the monkey hand (5), are accompanied by the articular nerves which terminate in the metatarsophalangeal joints from the plantar aspect. This intimate relationship between the sM arteries and articular nerves shows that the sM arteries of the monkey hand and foot and the human hand and foot are quite homologous. The sI, dM and dI arteries are not accompanied by such articular nerves in the monkey

foot, as in the human hand and foot (3, 4) and the monkey hand (5). As shown in Figures 1-4, the monkey foot has the contrahentes muscles. The sM and sI arteries descend dorsal to the contrahentes muscles, together with the articular nerves of the metatarsophalangeal joints. No artery was observed descending along the dorsal surface of the contrahentes muscles.

As described above and also as shown in our previous studies of the human hand and foot (3, 4) and the monkey hand (5), the sM, sI, dM and dI arteries exist together. This fact confirms that the sM, sI, dM and dI arteries are independent from each other.

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Received: July 21, 1987

Accepted: September 22, 1987

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