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TECHNICAL REPORT NO. 10016

LOCOMOTION IN NATURE

PART II: MODIFICATIONS OF THE FLY FOOT FOR HUMAN NEEDS

U.S. ARMY TANK-AUTOMOTIVE COMMAND LABORATORIES

January 1968

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by Claude B. Parker

Land Locomotion Division

TACOM

MOBILITY SYSTEMS LABORATORY

U.S. ARMY TANK AUTOMOTIVE COMMAND Warren, Michigan

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AMCMS CODE: 5016.11.844 PROJECT NO: 1-L-0-13001-A-91A

ABSTRACT

A search was undertaken to find out what work had been done and was available concerning the natural capability of flies and similar insects to walk on smooth inverted surfaces. The results show two general schools of thought on the physiological structure responsible for the special capability of the fly: (a) a gluing mechanism, and (b) suction cups. At present there exists insufficient data (photos, sketches, and chemical analyses) to closely duplicate the fly foot for man's needs. A general fly foot concept is outlined for use on a future walking machine, such as is being built for the Land Locomotion Division under contract by the General Electric Corporation. Possible adaptations of the fly foot are suggested in other fields.

ACKNOWLEDGEMENT

The author wishes to thank those experts listed in the Appendix of this report for their invaluable advice and guidance on the problem. Through the consensus of their knowledge the author has confidence to confirm the entomological portion of this report. Special thanks is given to Mr. Norman Mousseau for taking the high speed motion pictures of the flies and to Mr. Fred Summer for the illustrations.

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OBJECTIVE

This report is intended to evaluate the structure of the fly's foot with respect to possible modifications for human use, particularly in the field of mobility. It is not the function of this report to produce an answer to the question of how flies and similar light insects can stick to smooth inverted surfaces, but rather, by using whatever data are available, to propose uses for which this unique mechanism can be adapted.

BACKGROUND

The structure of fly feet is a logical consequence of a previous Land Locomotion Division report, Reference 11, as part of a larger in-house project on animal locomotion. The theme of this research, as explained in Reference 11, is in essence that nature does not use wheels or tracks for animals in off-road locomotion. Nature does use, however, a sophisticated system of levers which would intuitively lead one to believe that this time proven design would be the most efficient means of cross-country mobility. If this reasoning is in fact true, it would be prudent to study the structure and coordination of animals and insects before building a walking machine.

In the first Land Locomotion Division's animal locomotion report, Reference 11, large quadrupeds such as the moose were observed. The report suggests that the moose owes its mobility in muskeg and similar adverse terrain to its long, powerful, well articulated legs, with flexing ankles, and varying hoof prints. In addition, the moose, like the driver of the future walking machine, must be able to suddenly change course in order to avoid time consuming routes and disasterous obstacles. Although these characteristics of the animal which enable maximum efficiency may seem obvious, the human designer in his first attempts to emulate nature may become embroiled in an array of other technical problems. The end product will be functional, but not very efficient unless heed has been payed to the guidelines from nature.

INTRODUCTION

At the beginning of this project a library search was undertaken in order to locate all work that had been done concerning the fly foot. Of particular interest were sketches, microphotographs, and physiological reports which would shed light on what the fly foot looks like and how its adhering mechanism works. Several noted entomologists were consulted. A list of libraries and personalities consulted is included in the Appendix. The general consensus of opinion by the experts was that to their knowledge no one had as yet positively explained the ability of the fly to walk on smooth inverted surfaces. There were essentially two schools of thought on the subject, as will be explained later. The entomologists agreed that the information on the fly foot requested (reports, photos, sketches) would be difficult to find in one place. Several possible sources were suggested, but proved not really helpful for the purposes of this report.

The libraries yielded a variety of potential information: general entomology texts, periodicals, and journals. A good sampling of the sources checked or spot-checked is listed in the Appendix. The regular entomology texts were too general to be of much use and in many cases were a repetition of the original work on fly feet by Wigglesworth, for example, Reference 21. There were several books on insect physiology, but specific data relating to the problem could not be found. The journals, as in the case of the insect physiology texts, provided detail on many other aspects of the fly but not on the inverted walking ability. The periodicals were mainly concerned with taxonomic description of the many thousands of orders and species of insects. There were also articles on pest control and spread of disease, all of which had little bearing on the problem at hand and are mentioned just to show the extent of the search.

Since there seemed to be a dearth of information on the fly's walking habits, a study was conducted in which several flies were photographed alive in captivity with high speed motion picture cameras. Analysis of the photos reveal several important features of fly walking as discussed under observation.

Before proposing an adaptation of the fly foot, the subsequent pages will summarize some basic entomology relevant to the problem, existing theories of insect adhesion to smooth inverted surfaces, and personal observations from the high speed movies.

BASIC ENTOMOLOGY RELEVANT TO THE PROBLEM

In the initial planning of this study only the housefly was considered as an upside-down walking candidate. Although there was little information on the fly, it was readily discovered that many other insects have this ability. Several of these insects include (from Reference 10):

	Order	Example
a.	Diptera	Housefly, Gnat
b.	Hemiptera	Rhodnius, Platymeris
c.	Hymenoptera	Bee, Wasp
d.	Coleoptera	Beetle
e.	Orthoptera	Cockroach
f.	Collembola	Springtail

In addition, some insect larvae are known to secrete a sticky substance in order to glue themselves to a surface while hatching. (See Reference 9). This fact should be recalled when mention is made of flies using "glue" to stick to inverted smooth surfaces.

As intuitively expected, the extent of the insect world is enormous. There are some 600,000 known species of insects, each of which has different legs, body parts, head, wings, nervous system, and motions. These characteristics for each specie depend, in addition, upon its phase in the metamorphic cycle and in some cases upon its sex. There is no reason, therefore, to believe that the same adhering mechanism used for one fly is used by all insects or, for that matter, in even another fly. Surely the wide variety of insects leaves much room for research in the field of adhering mechanisms alone.

Taxonomically speaking, insects are classified under phylum Arthropoda (jointed or segmented) and Class Hexapoda (six-legged).

All insects have three distinct parts: head, thorax, and abdomen. The thorax is made of three minor segments or sclerites on each of which is attached a pair of legs. Insects are entirely covered with a stiff chitinous material called the cuticula which serves as an exoskeleton. The cuticula has varying degrees of rigidity depending on its body location and time after molting. Flexibility of the body and legs is provided through connections in much the same manner as a suit of armor.

A distinguishing feature of all insects is that they have six legs. Each leg usually has five distinct segments: coxa trochanter, femur, tibia, and tarsus, as shown in Figure 1. The segments are hollow cylinderical tubes with nerves and muscles running along the periphery of the segment. The articulated legs of the fly are capable of independent movement. Contraction of the leg is a muscular process while return to the extended position is accomplished by elasticity of the cuticula.

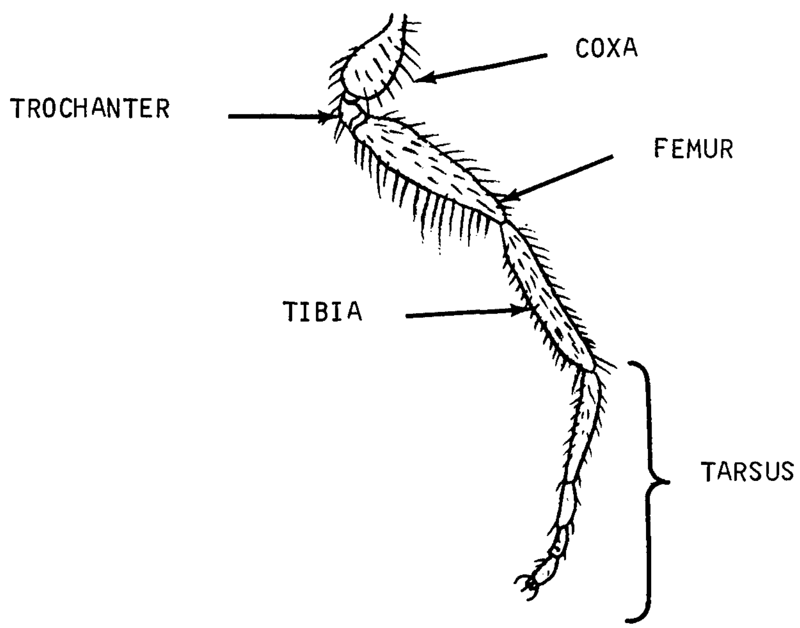

Figure 1.

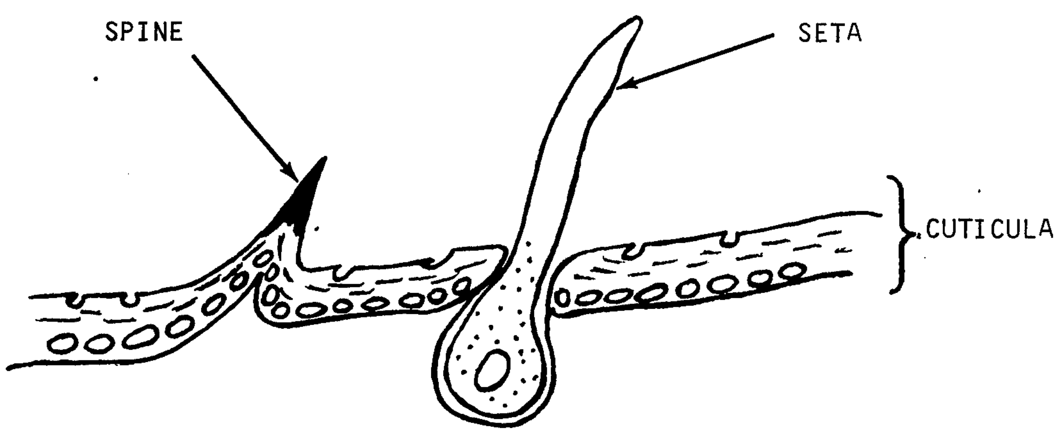

Figure II.

All leg segments are covered with "hairs", setae and spines, which have taxonomic significance in some orders of flies. Figure 11 from Comstock, Reference 4, illustrates the difference between spines and setae. Comstock is quick to point out, however, that in many places in the literature the terms are used indiscriminately without alluding to the distinction that the setae are mainly sense organs. The importance of setae to locomotion, therefore, is more for the purpose of guidance rather than as a supporting or traction mechanism. The spines consist of two types: primary and secondary. The larger primary spines serve as points of contact to transmit the load and propulsive forces. The smaller, secondary spines, are used to protect the still smaller setae.

EXISTING THEORIES

This study found that there were essentially two schools of thought on how insects, specifically flies, are able to walk on inverted surfaces: adhesion by glue and adhesion by suction cups. It is of interest to note here that the gripping force of some insects to hold others either for killing or copulation, Reference 8, has been measured and found to be extremely large. The effectiveness of the adhesive organ, however, in these cases is due in part to the hooking ability of the foot to the asperities of the victims cuticula.

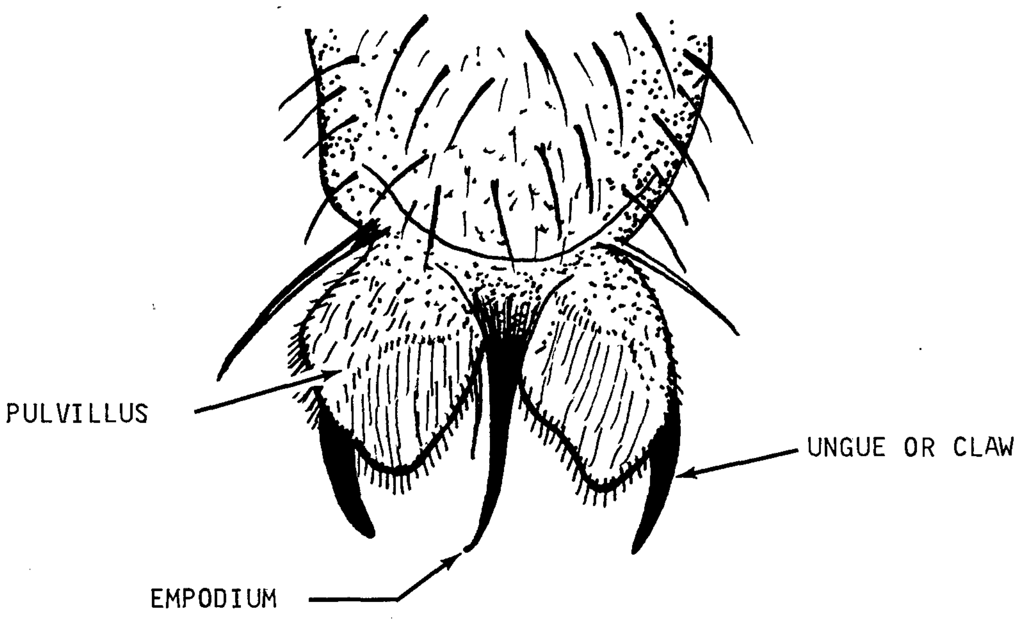

Figure III.

Figure III, as taken from Reference 20, is a sketch of a typical fly foot. For those who follow the glue theory, the pulvilli, as shown in Figure III, are fleshy adhesive organs covered with tiny tenant hairs. The hairs are hollow and exhude a glue upon contact with a smooth surface. Larger insects would naturally need a greater footprint area or stronger glue to support their greater weight. Apparently there is a maximum body size and weight because all upside-down walkers are relatively small. Wigglesworth, Reference 21, one of the early workers and most referred to, supports the "glue" theory.

The suction cup theory proposes that a liquid, not necessarily a glue, is secreted around the hairs and an air tight chamber is created to anchor the foot to the surface by atmospheric pressure. One proponent of this theory, Curran, emphatically states that the fly uses a suction cup and shows a picture, Reference 5, looking down on a fly on an inverted glass plate. The photo shows a transparent mass around the fly's foot which in fact could be the cup or a mass of glue. In none of the work was mention made of finding footprints as one would expect to find if the fly secreted a glue.

It seems quite likely that a combination of both glue and atmospheric pressure could be used to explain the sticking phenomenia. In order to answer the question precisely, a study such as the one by Gillette and Wigglesworth, condensed below from Reference 10, would have to be made. Although this study concerns the climbing ability of the bug, Rhodinius, it may serve as a valuable guide for future work on the fly.

OBSERVATIONS BY GILLETTE AND WIGGLESWORTH ON THE ADHESIVE ORGAN OF THE RHODNIUS

The adult Rhodnius, a true bug, has distinct adhesive organs on the lower end of the tibia of the two foremost legs. Researchers Gillette and Wigglesworth describe the organ, Figure IV as an elastic sack filled with fluid and covered with tenant hairs.

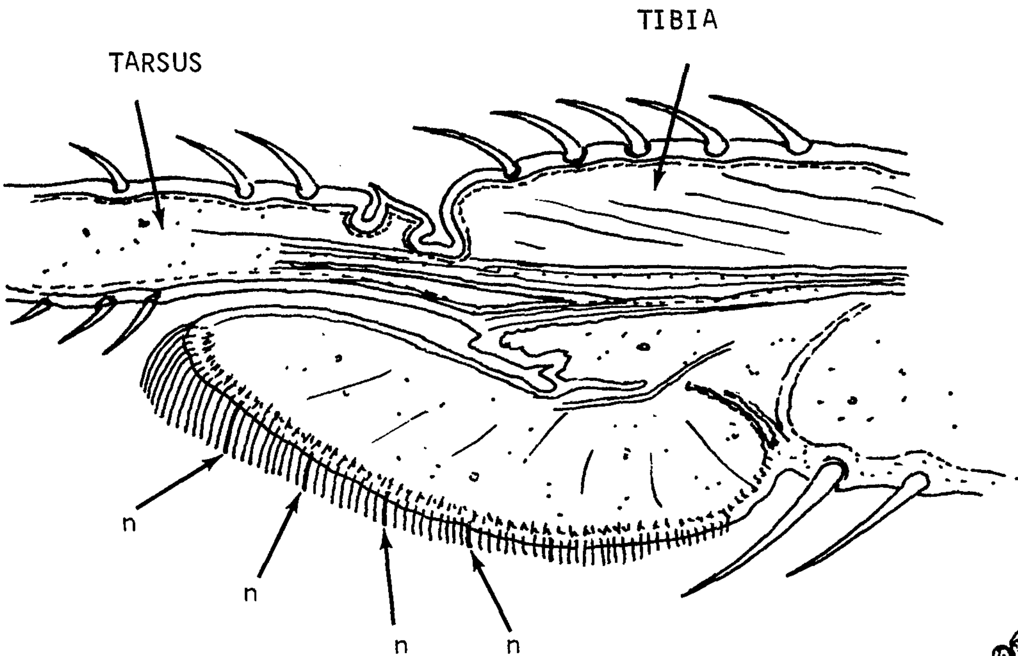

Figure IV.

n - nerve fiber
sh - sensory hair
ah - adhesive hairs
gc - glandular cells
sp - chitinous sole plate

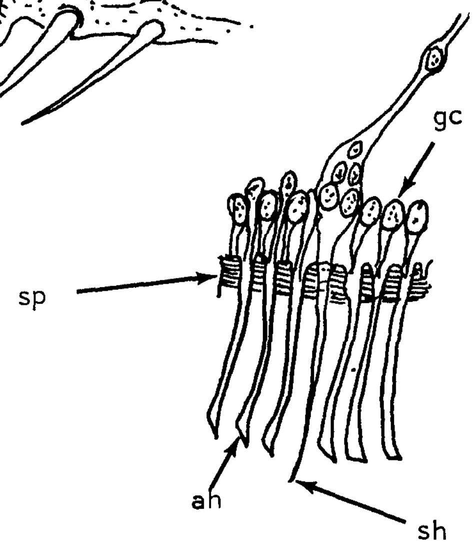

Figure IVa.

Microscopic analysis reveal the organ is constructed as sketched in Figure IV and Figure IVa.

Experiments with the Rhodnius on an inclined smooth glass surface indicate that the bug can climb in a near vertical position, but needs a rough surface such as cork in order to walk upside-down.

Further study indicates that the adhesive organ is of little use when climbing down. Footprints are left when the insect walks down the glass, but not in the upward direction. A possible explanation follows from lubrication theory which proves that the "hold" position, shown in Figure V, offers greatest frictional resistance to sliding. The sketch in Figure IVa clearly shows the hairs are designed for maximum holding ability.

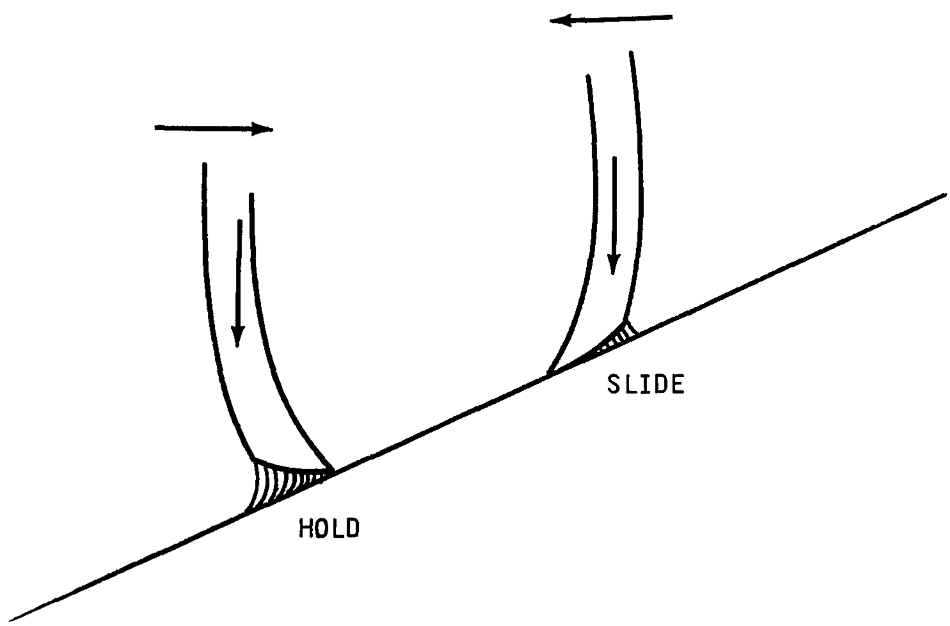

Figure V.

GENERAL OBSERVATIONS

The following observations were made at the Land Locomotion Division concerning the general nature of flies as they prepare to, and walk on smooth inverted glass surfaces.

a. The fly is not able to stick to all surfaces.

b. Before attempting to walk on a slippery inverted surface the fly rubs its two forefeet behind his eyes and appears to "spit" on them. He then methodically rubs his two rear legs against the top of his wings. See Figure VI.

Figure VI.

The purpose of leg rubbing may be to stimulate and/or spread the adhesive over the entire tarsal segment. The rubbing could also create an electrostatic force.

c. The leg of the fly, especially the tarsus, has extreme flexibility in all directions.

d. All legs are capable of independent motion.

e. The sequence of leg movements seem to depend upon the particular maneuver and is sometimes coordinated with wing movements. Figure VII shows the fly shifting wing positions as it begins to ascend from a horizontal to a vertical surface.

Figure VII.

f. While walking upright most of the weight is supported on the entire length of the tarsal segment. See Figure VIII. In the inverted position the fly uses the more distal end of the leg, although on extremely smooth surfaces the fly may drag its rear legs presumably for more contact area and adhesion.

Figure VIII.

g. When observing the fly under a microscope on a smooth inverted surface, obvious white specks appear at the tip of the fly's foot. These specks are not apparent when the fly is walking right side up. See Figure IX.

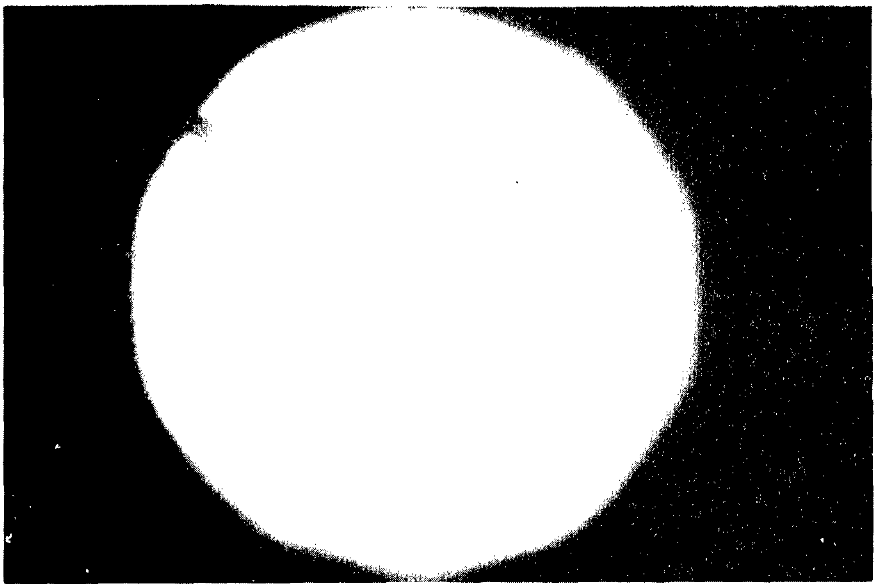

Figure IX.

h. The legs of the dead fly, Figure X, assume a straight alignment since the live nerves and muscles are needed for contraction. The legs automatically extend through the elasticity of the cuticula.

Figure X.

PROPOSED ADAPTATION OF THE FLY FOOT TO THE WALKING MACHINE

After studying the flys foot, significant features can be seen in its construction that would be well worth using in the design of a foot for a future walking machine. Figure XI is a sketch of a proposed concept for such a foot. The following section is a discussion of this concept and why it is better than a plain featureless pad at the end of the leg.

Under normal walking conditions on a firm, smooth, flat or gently sloping surface, the foot would contact the ground on an inflated rubber bladder shown in Figure XII. Besides providing traction, the rubber bladder would serve to cushion the impact as the walking machine transfers its weight to that leg.

A torsion bar or spring is placed at the ankle to allow the foot to pivot $\pm$ 20° from the horizontal when climbing or decending a sloped surface. Figure XIII shows the foot on a rising slope in two positions depending upon the inclination of the load. Note the heel is purposely pointed down to act as a spade when required.

The rubber bladder is capable of being inflated and deflated through an air pressure/vacuum line as dictated by the needs of the driver. When walking on a firm but slippery surface, the bladder can be deflated by the vacuum facility and withdrawn into the hollow of the foot. A firm rubber lip protruding from the perimeter of the hollow would in essence form a suction cup, depicted in Figure XIV, to give the foot added traction.

To facilitate walking in soft soil an air line is connected which supplies pressure under the foot. The vacuum is thus broken and the foot can be lifted with considerably less effort. Figure XV sketches this condition.

Retractable claws are placed on the front of the foot. The claws can be extended for gripping as needed, for example, in areas of irregular undercover and deadfall. See Figure XVI. It is suggested that the claws be retractable and capable of reaching beyond the level of the foot rather than fixed at the foot level. Since the claws would only be used under certain conditions, a longer and deeper design would be more effective. The retracted position of the claws would protect them against breakage while not in use.

The use of a bladder under the foot has certain mobility advantages. On a stoney ground the soft bladder will absorb all the minor bumps to keep the foot level. On a hard surface the weight is supported on the bladder when inflated and on the suction cup and possibly the heel or claws when deflated. The bladder permits a variable contact pressure. On a soft surface the foot sinks, thusly shifting the weight from the bladder to the entire foot and hence decreasing the contact pressure.

The suggested shape of the footprint is based essentially on the fly, but is similar to many animal paws. It is recommended that such a pattern be used rather than a simple circle, square, rectangle or other basic geometric form because this is the footprint Nature has adopted over many long years of experience.

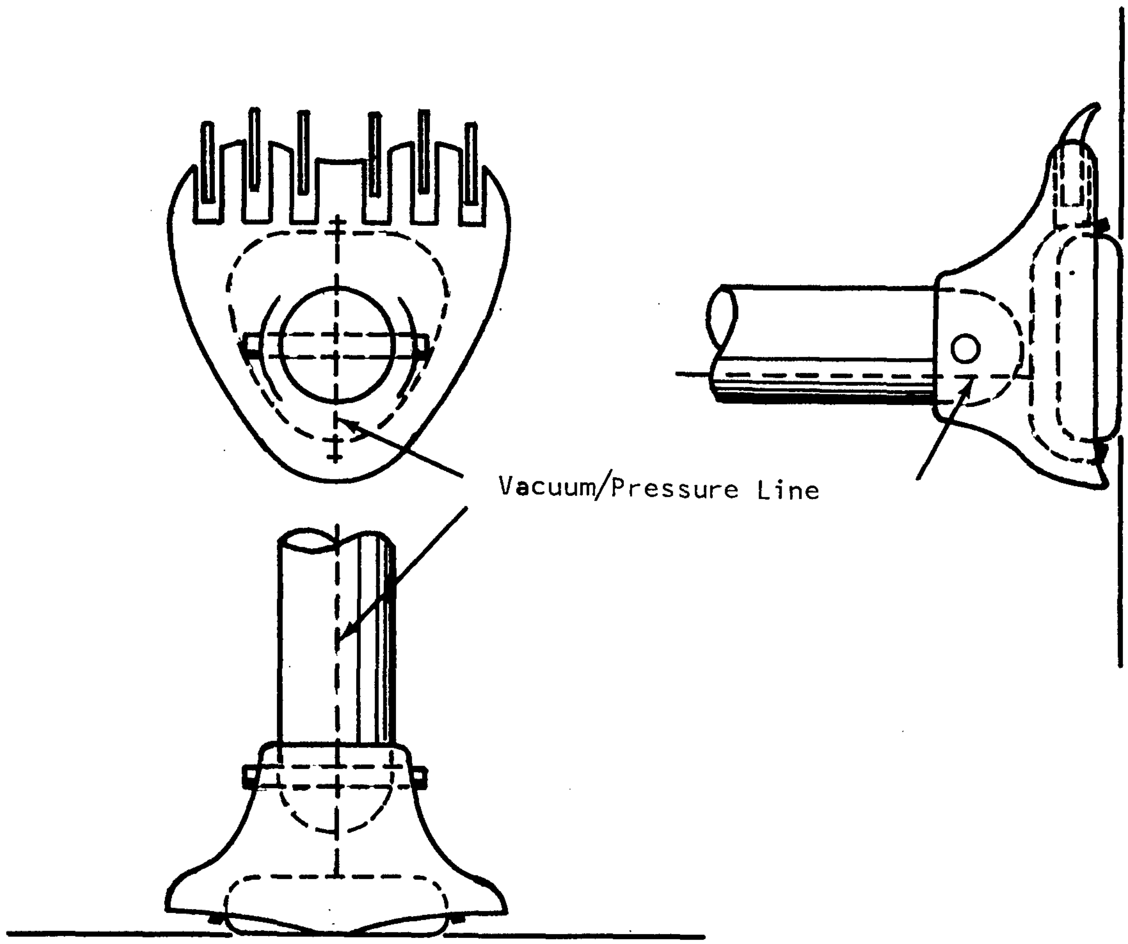

Figure XI.

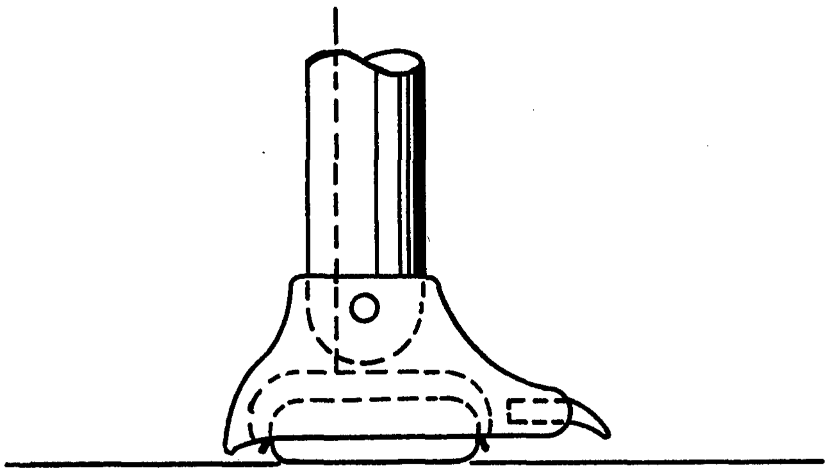

Figure XII.

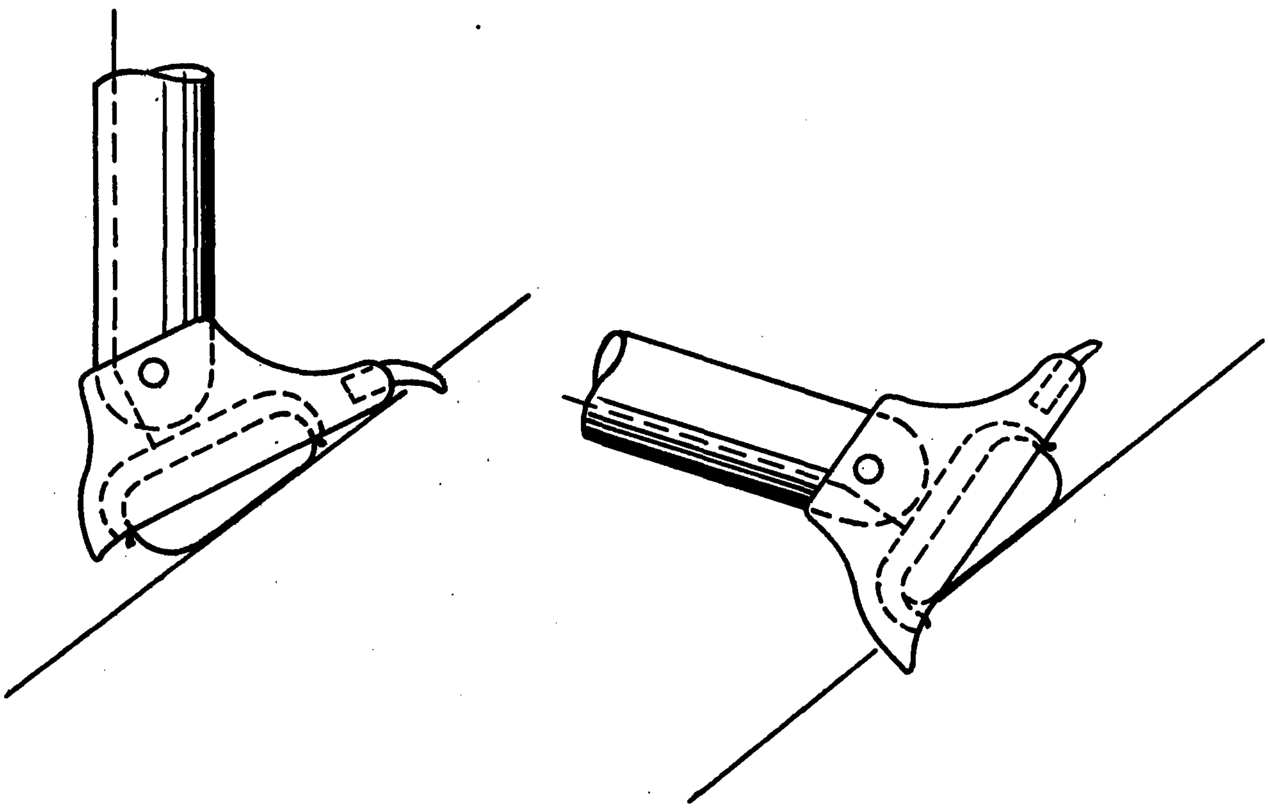

Figure XIII.

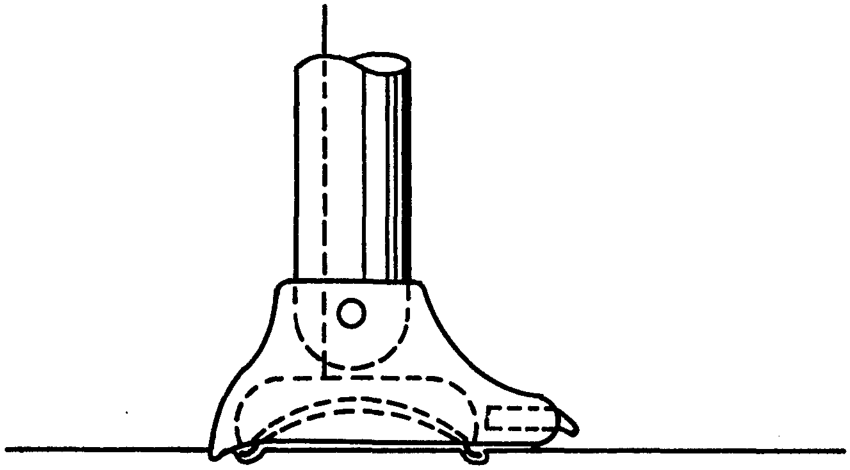

Figure XIV.

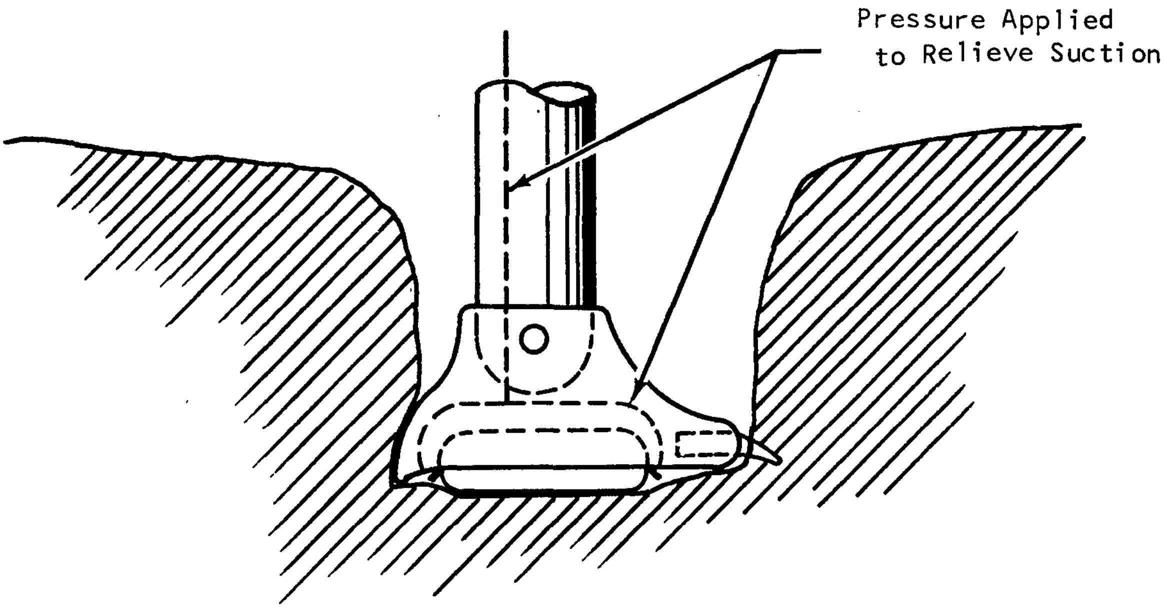

Figure XV.

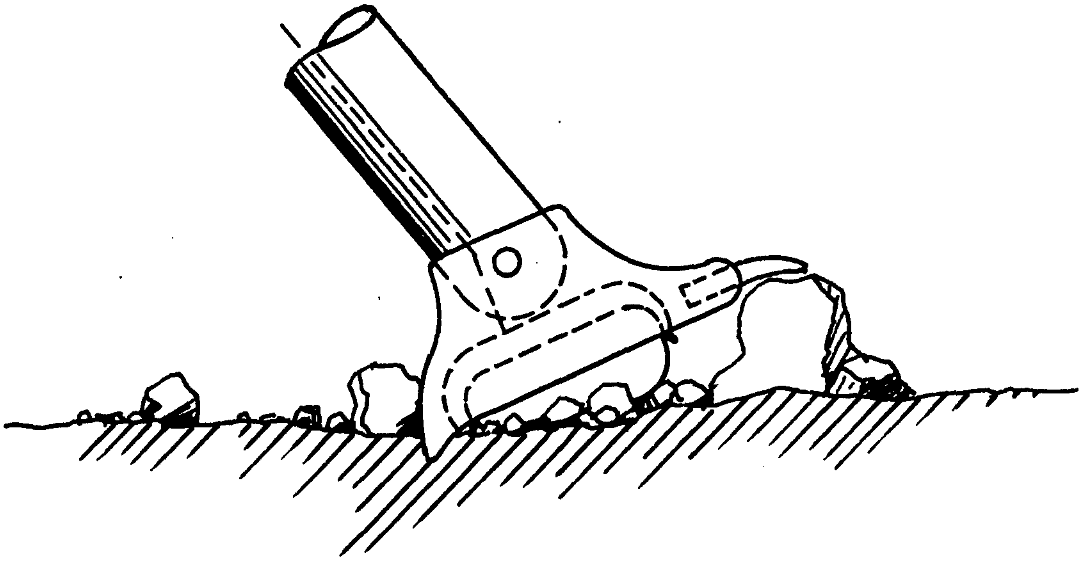

Figure XVI.

DISCUSSION

Although the main consequence of this report is the proposal to use the fly foot concept for the walking machine, there are doubtless numerous other applications for an adhering mechanism that would possibly stem from a detailed analysis of the foot. For example, the following possibilities are suggested.

a. A fly foot similar to the one proposed for the walking machine could be modified to replace the pads on the tracks of track laying vehicles. Although the air pressure/vacuum features would be of limited use, the footpring and claws would permit greater traction in most off-road conditions.

b. The adhering mechanism would be extremely useful to astronauts in their weightless space environment. Inside the space ship the mechanism could be based on the vacuum principal. Outside the space ship and in the total vacuum of deep space a glue mechanism would have to be devised.

c. Research scientists studying the habits of animals need a good method of inconspicuously attaching instruments and sensing devices to the skin of the subject. It is conceivable that a fly foot concept could be used, for instance, to monitor the location of fish and wild life.

d. In addition to countless other obvious uses for a good adhering mechanism, the fly foot study may generate a wealth of knowledge concerning methods by which the insects pick up and transmit disease.

CONCLUSIONS

The question of whether the fly uses "glue" or "suction cups" to stick to smooth inverted surfaces is still unresolved. Little literature and data on the fly's foot exist which would be of much use to exactly duplicate the mechanisms of the foot for human needs. The question of adhering at this point is irrelevant to a walking machine since the machine is not intended to stick to inverted surfaces. Existing knowledge of the foot such as shape, claws, and appropriate pressure/vacuum facilities, however, can be directly applied to improve the suspension traction, and flotation of a walking machine. The fly foot as outlined will be far superior for adaptation to a walking machine than a simple rigid pad at the end of the leg.

RECOMMENDATIONS

In light of the lack of information on the fly's adhering mechanism as shown by the search and its potential use, it is recommended that an effort be made to determine exactly how small insects are able to stick to smooth inverted surfaces. The research should include a detailed microscopic analysis with sketches and photographs of all pertinent parts of the foot. If a glue is used, a chemical analysis should be made and the substance synthesized and tested for holding ability. If a suction cup is used, detailed drawings should be made to explain its functioning and enable its duplication. In addition, work should be done to elucidate the control of the mechanism with respect to the nervous system. In conjunction with and after this research, efforts should be made towards adapting the findings to human needs.

It is recommended that a foot similar in concept to the one proposed in this report be designed for the walking machine. The exact details of the design will depend upon the machine, but the fly foot as outlined will be far superior to a simple rigid pad at the end of the leg.

APPENDIX

1. <u>List of Libraries Searched</u>

   a. Wayne State University

   b. University of Detroit

   c. University of Michigan

   d. Detroit Public Library

   e. Defense Documentation Center (Past 50 years).

2. <u>Partial List of Personalities Consulted</u>

   a. R. D. Alexander, Biology Department, University of Michigan.

   b. D. DeGuisti, Biology Department, Wayne State University.

   c. Colonel J. M. Geary, Armed Forces Pest Control Board, Forest Glen Section, Washington, D. C.

   d. Major T. J. Keefe, Department of Army, Fort Detrick, Frederick, Maryland.

   e. K. V. Krombein, Chairman, Department of Entomology, Smithsonian Institute, U. S. National Museum.

   f. J. La Breque, U. S. Entomologist, Gainsville, Florida.

   g. H. F. Schoof, Biology Section, Department of Health, Education, and Welfare, Savannah, Georgia.

   h. R. J. Smith, Biology Department, University of Detroit.

   i. L. S. West, Professor Emeritus, Northern Michigan University.

   j. Curator of Entomology, American Museum of Natural History, New York City, N. Y.

3. List of Sources Spot-Checked (Limited Value)

Journals:

a. American Entomology Society, Transactions

b. American Scientist

c. British Museum of Natural History, Entomology

d. Brooklyn Entomology Society

e. Bulletin of Entomological Research

f. Canadian Entomologist

g. Entomologist

h. Entomological Society of America

i. Journal of Entomology

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DOCUMENT CONTROL DATA - R&D	
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)	
1. ORIGINATING ACTIVITY *(Corporate author)* Land Locomotion Division, AMSTA-UL	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP
3. REPORT TITLE LOCOMOTION IN NATURE. PART II: Modifications of the Fly Foot for Human Needs.	
4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*	
5. AUTHOR(S) *(Last name, first name, initial)* PARKER, CLAUDE B.	

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 1968	28	23

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report No. 10016
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	
10. AVAILABILITY/LIMITATION NOTICES	
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13. ABSTRACT

A search was undertaken to find out what work had been done and was available concerning the natural capability of flies and similar insects to walk on smooth inverted surfaces. The results show two general schools of thought on the physiological structure responsible for the special capability of the fly: (a) a gluing mechanism, and (b) suction cups. At present there exists insufficient data (photos, sketches, and chemical analyses) to closely duplicate the fly foot for man's needs. A general fly foot concept is outlined for use on a future walking machine, such as is being built for the Land Locomotion Division under contract by General Electric Corporation. Possible adaptations of the fly foot are suggested in other fields.

DD FORM 1 JAN 64 1473

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