論　文　内　容　の　要　旨
Synopsis of Thesis

氏　名 Name	平松　佑一
論文題名 Title	Control of Precision Grip Force in Lifting and Holding of Low-Mass Objects （軽量物体における精密把握運動時の把握力調節）

論文内容の要旨

〔目　的(Purpose)〕

Small objects are commonly manipulated using a precision grip with the tips of the index finger and the thumb. During the past few decades, considerable effort has been devoted by researchers in neuroscience to studying sensori-motor function involved in this simple mode of grip for lifting, holding, and transporting objects. Researchers commonly used an instrumented movable object, aiming to evaluate finger forces normal (grip force) and tangential (lift or load force) to the grip surface. The instrumented object used by these researchers commonly had a mass of a few hundred grams or more. The effect of a small mass (< 100 g) of the object in normal-gravity conditions on grip-load force coordination had not been examined by any of the previous researchers. The present study was conducted to examine variables of grip-load force coordination while healthy adults lifted and held a force-sensor-equipped movable object with a mass ranging from very small (6 g) to moderate (200 g) for slippery (rayon) and non-slippery (sandpaper) surface conditions. Using an object with the same dimensions and grip surfaces as those of the instrumented test object, a weight discrimination test was also performed by the subjects. In addition, changes in the finger-surface contact area and the finger pad indentation with grip force were also examined.

〔方法ならびに成績(Methods/Results)〕

Eight healthy females and nine males (18 to 30 years: mean = 22.2 years) served as subjects in this study. An extra-light force sensor installed object (6 g) was developed, which allowed the measurement of grip (normal) forces by the thumb and index finger, and load force. The apparatus was lifted to a height of about 5 cm above as test table, and it was held in the air for about 10 sec. It was then dropped by slowly separating the fingers to measure grip and load forces at slip moment. Fourteen apparatus mass conditions: 6, 8, 10, 14, 22, 30, 40, 50, 70, 90, 110, 130, 150, and 200 g, were tested while the grip surface was set in a non-slippery sandpaper or a slippery rayon. Each subject performed 8 trials for each of the 14 mass conditions for each of the two surfaces. From the measured grip and load forces, grip force for static holding, slip force (slip moment grip force), a static grip force/load force ratio, grip force safety margin (grip force − slip force) relative to the static grip force, the coefficient of static friction, and static grip force variability were evaluated. Additional tests included grip force-related changes in the contact area of the finger skin, and the stress-strain relationship of the fingertip during gripping of an object were performed by each of the subjects. In addition, nine subjects underwent a weight discrimination task using two light grip objects having the same dimensions as the grip force measurement apparatus. Four sets of test mass (10, 24, 48, and 112 g), with each set comprising 9 levels of test mass and one standard mass, were used to find a just noticeable difference (JND) in object mass within each set.

For each surface condition, the static grip force was modulated in parallel with load force while holding the object of a mass above 30 g. For objects with mass smaller than 30 g, on the other hand, their parallel relationship was changed, resulting in a progressive increase in a grip-to-load force (GF/LF) ratio. The rayon had a higher GF/LF force ratio across all mass levels. The proportion of safety margin in the static grip force and normalized moment-to-moment variability of the static grip force were also elevated towards the lower end of the object mass for both surfaces. The contact area and skin deformation sharply decreased when the applied grip force was below 1 N, and the decrease was even sharper below a grip force of 0.5 N. Weight discrimination test showing a clearly higher Weber fraction with a lighter object. The ability to discriminate heaviness held by the fingers was thus not proportional to the object mass.

〔総　括(Conclusion)〕

These findings indicate that the strategy of grip force control for holding objects with an extremely small mass differs from that with a mass above 30 g. The data for the contact area, skin indentation, and weight discrimination suggest that a decreased level of cutaneous feedback signals from the finger pads could have played some role in a cost function in efficient grip force control with low-mass objects. The elevated grip force variability associated with signal-dependent and internal noises, and anticipated inertial force on the held object due to acceleration of the arm and hand, could also have contributed to the cost function.

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論文審査の結果の要旨及び担当者

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論文審査の結果の要旨

本研究は、これまで十分な検討が加えられて来なかった指先での軽量物体の把持運動における把握力・持ち上げ力協調戦略について明らかにすることを目的とし、健常成人を対象として把握物体の重量を6ｇから200ｇまで、また把握面の摩擦状況をレーヨンとサンドペーパー面に変化させる中での力調節、重量弁別能力、指先の物理特性変化などを詳細に検討している。その結果、把握面状況に関わらず軽量域になる程、把握力/重量比が増大すること、その際の把握力の安全領域および指先の滑り係数、把握力の変動係数も増大すること、重量弁別機能が低下すること、指先の把握面接触面積および変形量が急激に減少すること、などの新たな知見を報告している。論文では、これらの結果に基づき指腹部からの感覚情報量と中枢からの運動指令の関係についての考察も十分になされている。また、超軽量（6ｇ）で把握力および持ち上げ力を同時に計測できる装置の開発も新たな試みであり、それに関しても成功を成し遂げている。よって本論文は、精密把握運動の把握力制御に関するこれまでの知見を明らかに発展させ、さらに新たな研究が可能となる測定装置の開発にも成功していることは十分に評価できるものであり、博士（医学）の学位授与に値するものである。